TAMPERE UNIVERSITY OF TECHNOLOGY

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Modeling, Performance Evaluation and Suitability Study of Zigbee Technology for Machine-to-Machine Communications Applications

Master of Science Thesis

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ABSTRACT

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The number of nodes in current communication networks, specially in wireless technology, is increasing day by day. At the same time, the communication concept is changing from being mainly human to human (H2H) toward machine to machine (M2M). On the other hand, the objects and devices will become part of future Internet in which the concept of connectivity will change from anywhere, anytime for anyone to anywhere, anytime for anything by introducing Internet of Things (IoT). Therefore, it is expected that billions of objects will communicate to each other physically and virtually through the Internet. When these numbers of devices, usually very high, are connected to the Internet to form the IoT network, the first challenge is to adjust the basic connectivity and networking layers between them. On the other hand, end point users must operate with battery for many years since replacing them is impossible due to the high number devices. Currently, we witness an increasing momentum for wireless industry to explicitly take into account the key M2M requirements, such as lower complexity, reduced implementation and operation costs, broader coverage range and higher energy efficiency. The IEEE 802.15.4 standard is presently being used for wireless sensor networks and ZigBee applications characterized by similar requirements as in IoT and M2M applications. The ZigBee technology based on IEEE 802.15.4 standard is mainly targeting LR-WPAN applications.

Due to importance of wireless sensor networks (WSN) in future M2M communications and because of the lack of comprehensive study of IEEE 802.15.4 in different frequency bands and different channel scenarios, this thesis evaluate the performance of the IEEE 802.15.4 using system level simulator developed during this work. The performance evaluation is carried out in terms of network throughput, energy consumption, and end-to-end delay. In addition, the performance comparison is accomplished between slotted IEEE 802.15.4 and IEEE 802.11ah (one of the most promising candidate standard for the IoT applications).

The results show that the IEEE 802.15.4 is a suitable standard in terms of energy consumption in congested networks but not in throughput point of view.

PREFACE

The research throughout this Master of Science Thesis work, "Modeling, Performance Evaluation and Suitability Study of Zigbee Technology for Machine-to-Machine Communications Applications," is conducted in the Internet of Things program of TiViT (Finnish Strategic Center for Science, Technology and Innovation in ICT), funded by the Finnish Funding Agency for Technology and Innovation (Tekes). The work is also financially supported by Renesas Mobile Europe Ltd. The research work was accomplished during the year 2012-2013 at the Department of Electronics and Communications Engineering, Tampere University of Technology.

First of all, I would like to express my gratitude to my supervisor Professor Mikko Valkama for giving me the opportunity to work in his research group and for his continuous support of my M.Sc. study and research. I would also like to thank my supervisor Dr. Ali Hazmi who has always been there to listen and give me advices.

I am also very grateful to my colleagues at office and my friends in Tampere University of Technology for helping me and supporting me during the work.

I am also thankful for my dear parents Nowruzali and Tabarze for their strong encouragement, unconditional love and belief in me. Thank you for supporting me every step of the way and constantly being there for me. I could not thank you enough for all that you have done for me and sorry for being away from you.

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Tampere, October 2013

Behnam Badihi

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TERMS AND DEFINITIONS OR LIST OF SYMBOLS AND ABBREVIATIONS

AP	Access point
ASK	Amplitude shift keying
BI	Beacon interval
BO	Beacon order
BPSK	Binary phase shift keying
BSS	Basic service set
CAP	Contention access period
CCA	Clear channel assessment
CCK	Complementary code keying
CFP	Contention free period
CSMA-CA	Carrier sense multiple access with collision avoidance
CTS	Clear to send
CW	Contention window
DCF	Distributed coordination function
DIFS	Distributed interframe space
DS	Distributed system
DSSS	Direct sequence spread spectrum
ED	Energy detection
ESS	Extended service set
FFD	Full function device
FHSS	Frequency hopping spread spectrum
GFSK	Gaussian frequency shift keying

GTS	Guaranteed time slot
H2H	Human to human
IBSS	Independent basic service set
IFS	Interframe space or spacing
IoT	Internet of things
L2CAP	Logical link control and adaption protocol
LIFS	Long interframe spacing
LMP	Link manager protocol
LR-WPAN	Low rate wireless personal area network
LQI	Link quality indication
M2M	Machine to Machine
MAC	Medium access control
NB	Number of backoffs
OFDM	Orthogonal frequency division multiplexing
OQPSK	Offset Quadrature Phase Shift Keying
OSI	Open system interconnection
PCF	Point coordination function
PDA	Personal digital assistant
PHR	PHY header
PHY	Physical layer
PLC	Power line communication
PPDU	PHY protocol data unit
RFD	Reduced function device
RFID	Radio frequency identification
RTS	Request to send

SD	Super-frame duration
SIFS	Short interframe spacing
SHR	synchronization header
SSCS	Service specific convergence sublayer
TDD	Time devision duplex

1. INTRODUCTION

The evolution of the wireless technologies and the remarkable development of the wireless network services have converted the wireless communications to an ubiquitous means for exchanging data through many different domains. Everything is turning to wireless. The captivation of mobility, accessibility and flexibility make wireless technologies a dominant method of exchanging all sort of information. Satellite televisions, cellular phones, cordless telephones, PDAs, and Wi-Fi are widely-known applications of the wireless technologies. The wireless research field is swiftly developing in the communication area and it provides a wide variety of applications under different topologies.

During the past decade the number of wireless devices are dramatically increasing. Recently, the idea of connecting the heterogeneous objects form different networks has brought the new concept of the connectivity. This new concept named Internet of Things (IoT) introduces the unique aspect to the communication world in which connectivity will be available anywhere, any time for any thing. IoT will enable the interoperability of heterogeneous applications, extending from smart phones and wireless sensors up to network-enabled physical objects (for instance, RFID, smart visual tags, smart grid) through universally integrated communications platforms [1].

In nearly the parallel way, machine-to-machine (M2M) technology has recently emerged to enable direct communications for heterogeneous devices through existing mobile operator network infrastructures in the IoT, for instance, Third Generation Partnership Project's Evolved Packet System (3GPP's EPS). This technology is highly promising enabler for developing a solution in the area of IoT applications extending from transportation, health-care, ambient assisted living, smart energy, smart utility metering, supply and provisioning, city automation, intelligent tracking, manufacturing, and so forth [2].

One of the major applications of the M2M system is wireless sensor networks. Wireless Sensor Networks will enable a wide range of new applications, for instance, home automation (security, lighting control, access control, temperature control), consumer electronics (TV/VCR/DVD/CD remote control), industrial automation (e.g. asset management, process control, environmental control, energy management) and personal health care (body sensor networks).

However, for this to become a reality, many new problems and challenges must be overcome in WSNs as their paradigm differs from traditional wireless networks. There is the need for low cost devices enabling large-scale networked embedded systems (as there can be hundreds or thousands of nodes scattered in large regions) and energy requirements that impose low communication rates and ranges and low duty cycles. Some of the most important challenges in WSNs are related to energy-efficiency, scalability, routing, mobility, reliability, timeliness, security, clustering, localization and synchronization.

The joint efforts of the IEEE 802.15.4 Task Group [3] and the ZigBee Alliance [4] have ended up with the specification of a standard protocol stack. This standard is intended for Low-Rate Wireless Personal Area Networks (LR-WPANs), an enabling technology for Wireless Sensor Networks (WSNs) [5], [13].

Investigating throughput, delay and energy consumption of IEEE 802.15.4 networks is essential to understand the fundamental characteristics of this protocol in the context of the IoT and M2M concepts. Several simulations-based studies, for instance, [6], [7], [8] investigate the delay, throughput, and energy consumption of IEEE 802.15.4. In addition, more recent analytical works, for example, [9], [10], [11], [12] are performed in terms of above-mentioned metrics.

However, there is a lack of study in non-ideal channel condition. And it should also be noticed that the above-mentioned works are performed in 2.4 GHz frequency band in datarate of 250 kbps. While standard itself support two other frequency bands operating in two different datarates. These bands are 915 MHz and 868 MHz with datarate of 40 kbps and 20 kbps, respectively. There is therefore lacking study and investigation of the IEEE 802.15.4 performance in those bands. This thesis covers the whole frequency bands with different data-rates in both ideal and non-ideal channels.

In this work, an overview of the IEEE 802.15.4 standard is described in Chapter 1. The basic concepts about this standard specially in PHY and MAC layer are illustrated. Many technologies like ZigBee use this standard in PHY and MAC layer as a baseline. In addition, CSMA-CA as an access mechanism of the standard is discussed in details.

Chapter 3 discuses about the emerging IoT and M2M technologies and essential requirements for M2M applications. This chapter illustrates the motivation for having the machine to machine technology and its pros and cons compared to traditional human to human technology. In addition, the M2M architecture and some of its corresponding use cases are also explained.

ZigBee as an important M2M enabler technology is compared with other M2M enabling technologies such as Bluetooth, RFID, and Wi-Fi in Chapter 4. These technologies are concisely introduced in this chapter and then the comparison study

is investigated in terms of different metrics. These metrics include RF channel, bandwidth, datarate, modulation,network size, coverage range, and transmission power, and etc.

To evaluate the performance of the IEEE 802.15.4, a system-level simulator is developed using the OMNeT++ tool and by further improving the existing INET-MANET framework. Hence, the introduction to OMNeT++ is discussed in Chapter 5 in order to illustrate the simulation environment. The remainder of the chapter is about the simulation model's settings, channel and path loss model.

The performance evaluation of the IEEE 802.15.4 comprises three metrics: throughput, energy consumption, and end-to-end delay. The above-mentioned metrics are performed for 2.4 GHz, 915 MHz, and 868 MHz frequency bands with datarate of 250 Kbps, 40 Kbps, and 20 Kbps, respectively. In addition, the performance of the IEEE 802.15.4 is compared with IEEE 802.11ah in terms of throughput and energy consumption. These results are investigated in Chapter 6. Finally, Chapter 7 concisely concludes the thesis work.

2. IEEE 802.15.4 OVERVIEW

2.1 Introduction

The low-rate wireless personal area networks (LR-WPANs) are characterized by extremely low power consumption, low data rate, and low complexity where the network can be easily installed and managed. The IEEE 802.15.4 is a standard which specifies the physical layer and medium access control sub-layer for LR-WPANs [14], [15]. This standard is supported by the IEEE 802.15 working group. It is the basis for the ZigBee specifications by further extending the standard to develop the upper layers. The higher layers above MAC sub-layer are not specified in the IEEE 802.15.4 [16]. Some of the most important characteristics of LR-WPAN are listed below:

- Data rates of 250 kbps, 40 kbps and 20 kbps.
- Star, peer to peer, and cluster-tree topology.
- Allocation of short address of 16 bit or extended address of 64 bit.
- Guaranteed time slots (GTS) for delay sensitive applications
- Low power consumption
- Acknowledgment support for reliable transfer
- Energy detection (ED)
- Channel access with carrier sense multiple access with collision avoidance (CSMA-CA)
- Link quality indication (LQI)
- 16 channels available in the 2450 MHz band, 10 channels available in the 915 MHz band, and 1 channel available in the 868 MHz band [17].

2.2 Components of IEEE 802.15.4 WPAN

A system using the IEEE 802.15.4 specifications includes several components. The most basic components in this standard are communication devices. Two types of device are defined in the standard: FFD (full-function device) and RFD (reduced-function device). FFD is able to communicate with other FFDs and RFDs while RFD can only communicate with FFDs. A network shall have at least one FFD to operate. FFDs can operate in three modes in the network: as a coordinator, or a PAN (personal area network) coordinator, or an ordinary device.

2.3 Network Topologies

The LR-WPAN standard supports three network topologies. These topologies are presented in Figure 2.1.

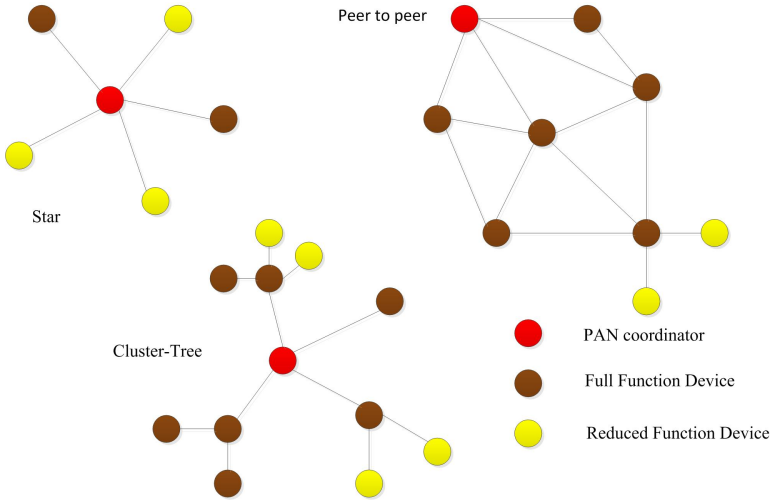


Figure 2.1: *Network topologies of the LR-WPAN system.*

2.3.1 Star Topology

In the star topology, the devices communicate with central device called PAN coordinator. Many applications such as home automation, personal computer peripherals, and games use this topology. The PAN coordinator is normally powered by continuous source of energy while other devices are mostly battery-powered. A network can be established with a FFD device when it start to be activated for the first time. Each FFD uses a special and unique PAN identifier which differentiate its network from any other networks in the zone of coverage. The PAN identifier allows multiple networks to independently operate in the same zone of radio coverage.

2.3.2 Peer to Peer Topology

Peer to peer topology also has a PAN coordinator but it differs from star topology in the sense that each device can talk with any other devices as long as they are in the coverage range of each other. Peer to peer network employs the multi-hop communication to send the data from source node to the destination node. This topology may lead to very complex topologies such as mesh topology. Many applications, for instance, industrial control and monitoring, wireless sensor networks, asset and inventory tracking, intelligent agriculture, and security utilize this topology. By employing the multiple hops, routing messages is possible from any device to any other device in the network. In addition, this topology has the characteristics of a self-organizing, and self-healing network which makes this topology more useful for ad-hoc network.

2.3.3 Cluster-tree Topology

The cluster-tree topology is a special case of peer to peer topology which comprises of many FFDs. In this topology, RFD can be attached to the network as a leaf node at the end of the branches. Any of the FFDs can behave like a coordinator to provide synchronization services to other coordinators and devices, however, the network only have one PAN coordinator at any time. The coverage area in the cluster-tree topology can easily be extended but on the other hand, it imposes the high latency to the delivered packets.

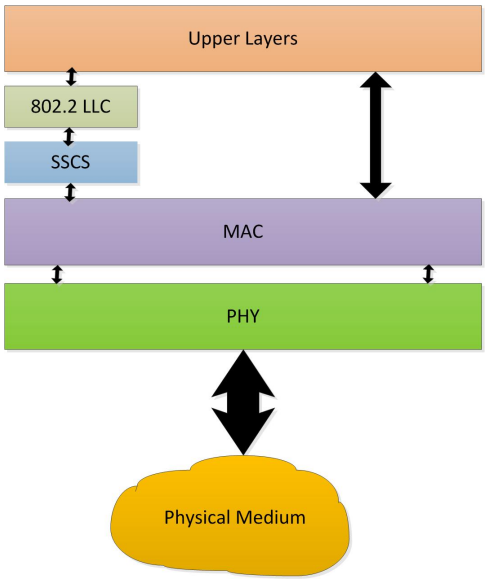


Figure 2.2: *LR-WPAN device architecture [IEEE 802.15.4 specifications].*

Table 2.1: *Frequency band and data rates.*

PHY (MHz)	Frequency band (MHz)	Spreading		Data parameters		
		Chip rate (kchip/s)	Modulation	Bit rate (kb/s)	Symbol rate ksym/s	Symbols
868/915	868-868.6	300	BPSK	20	20	Binary
	902-928	600	BPSK	40	40	Binary
868/915 (optional)	868-868.6	400	ASK	250	12.5	20-bit PSSS
	902-928	1600	ASK	250	50	5-bit PSSS
868/915 (optional)	868-868.6	400	O-QPSK	100	25	16-ary Orthogonal
	902-928	1000	O-QPSK	250	62.5	16-ary Orthogonal
2450	2400-2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

2.4 The Architecture of the LR-WPAN

The LR-WPAN architecture comprises of the blocks which are responsible for fully implementing the standard. Theses blocks, called layers, offer services for higher blocks. The layout of the layers is based on the Open system interconnection (OSI). Figure 2.2 shows the architecture of the LR-WPAN. As figure shows, the structure consists of the PHY layer, MAC sub-layer, network layer, LLC sub-layer, and application layer. The PHY layer contains the radio frequency transceiver along with low complex controller, and MAC sublayer, which allows access to physical medium with all type of transmission. The upper layer includes network layer which is responsible for network configuration, manipulation, and message routing, and finally application layer, which provides services for an application program to ensure that effective communication with another application program in a network is possible. The LLC sub-layer provides multiplexing mechanisms by accessing MAC sublayer through service specific convergence sublayer (SSCS). It allows for several network protocols to coexist within a multi-point network and transported over the same network medium.

2.5 PHY Layer

The main functions of the Physical layer are enabling and disabling radio receiver and transmitter, energy detection (ED), link quality indication (LQI), channel frequency selection, clear channel assessment (CCA) for CSMA-CA, and receiving and transmitting packets through the physical medium.

The frequency bands and data rates are shown in Table 2.1. According to the table, three different data rates are available in the physical layer. The supported data rates are 250 kbps, 40 kbps, and 20kbps which operate at 2.4 GHz, 915 MHz 868 MHz, respectively. In addition, two optional cases exist in 868 and 915 MHz frequency bands which use different data rates and modulations.

The higher order of modulation is employed to achieve the higher data rates. For instance, O-QPSK is used to achieve 250 kbps and BPSK is applied in 40 kbps and 20 kbps. In addition, the coverage area increases in lower frequency due to less propagation loss. On the other hand, the higher data rate provides higher

throughput with low message latency and low duty cycle.

Table 2.1 shows the frequency bands and supported data rates in IEEE 802.15.4 along with modulation type. The available channels for the different frequency bands in this standard are:

- 1 channel in 868 MHz
- 10 channels in 915 MHz
- 16 channels in 2.4 GHz

2.5.1 Modulation and Spreading

IEEE 802.15.4 employs modulation and spreading technique in PHY layer. In the following, the modulation and spreading for 2.4 GHz frequency band is explained. Spreading technique aids the coexistence of the IEEE 802.15.4 with other technologies utilizing the unlicensed frequency bands. In addition, it improves the receivers sensitivity and reduces the multipath effect, and increases the jamming resistance. IEEE 802.15.4 employs Direct Sequence Spreading Spectrum (DSSS) as a spreading method. In this method, every 4 bits of a PPDU are grouped together and mapped to a symbol. Then each symbol is mapped to a unique 32-bit sequence based on the lookup table. This 32-bit sequence is called the chip sequence or the pseudo-random

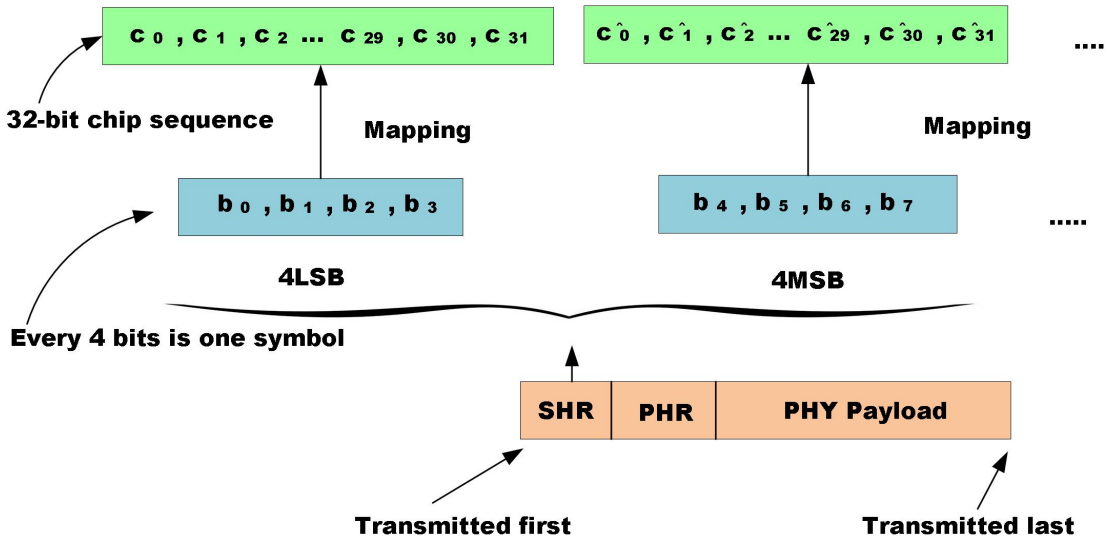


Figure 2.3: *The Signal Spreading in DSSS [54]*

noise (PN) sequence as well (see Figure 2.3). Effective bit rate in the air increases by the factor of eight, since each 4 bits of the actual data are mapped to a 32-bit chip sequence. By knowing the fact that bandwidth is proportional to bit rate, the bandwidth will also increase by the factor of eight. For instance, if the data rate is 250 kbps, after the spreading the bandwidth will increase to 2 MHz [54].

After despreading signal in the receiver, the energy of the signal will accumulate on the original bandwidth of 250 kHz, but the despreading will not have any effect on the noise level in the 250 kHz band. The effective SNR will increase in the result of increasing the signal energy without increasing the noise level. The SNR improvement is known as the processing gain . The processing gain is calculated as a ratio of the actual data rate to the chip rate . In the case of 2.4 GHz mode in IEEE 802.15.4, processing gain is equal to [54]:

$$ProcessingGain = 10 \times log_{10}\left(\frac{2\,Mbps}{250\,kbps}\right) \cong 9\,dB \tag{2.1}$$

Figure 2.4 shows the spreading and modulation for the IEEE 802.15.4 operated in 2.4 GHz frequency band.

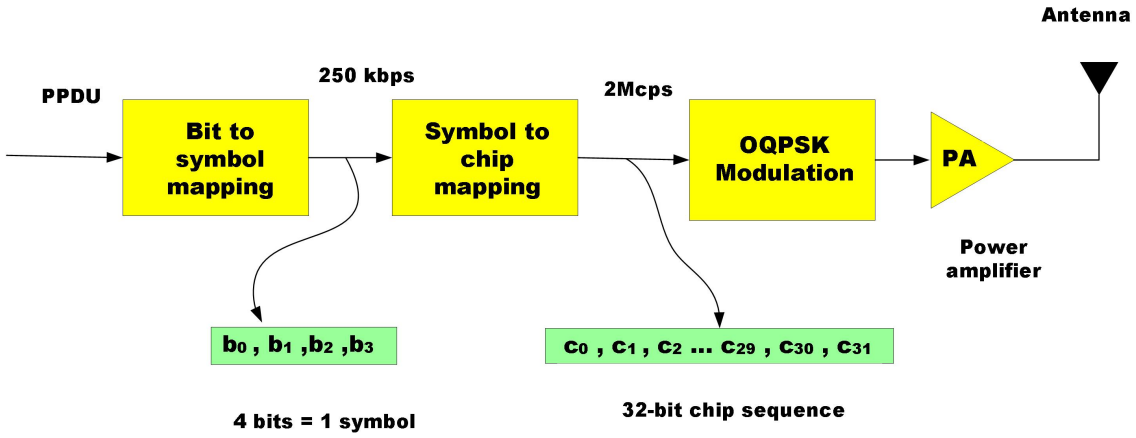


Figure 2.4: *The Spreading and Modulation for the 2.4 GHz [54]*

2.5.2 Energy Detection (ED)

Energy detection is a mechanism used by the physical layer in order to choose a proper channel for the network layer. The mechanism is based on the energy estimation of the received signal within the bandwidth of the WPAN channel. Energy detection is not meant for decoding or signal identification. The minimum ED value should detect the received power in less than 10 dB above the determined receiver sensitivity threshold and the maximum tolerance of the received power shall span at least 40 dB.

2.5.3 Link Quality Indication (LQI)

The quality of the link is sent by the physical layer as a feedback signal.The feedback contains the quality and the strength of the received packet by the physical layer.

Two methods can be applied for implementing this mechanism which are the ED measurement and signal to noise estimation. However, the combination of these two method can be employed as well.

2.5.4 Clear Channel Assessment (CCA)

Clear Channel Assessment is a logical function applied by the physical layers which determines the current state of the wireless medium to prevent collision. CCA can be implemented in three following methods:

Energy above threshold: The CCA shall utilize Energy detection (ED) measurement as a criterion for deciding whether the medium is free or busy.

Carrier sense only: The CCA shall report a busy medium in the case of detecting a carrier with the characteristics of the IEEE 802.15.4 standard regardless of the ED threshold.

Carrier sense with energy above threshold: In this criterion, the CCA shall report a busy medium in the case of detecting a carrier with the characteristics of the IEEE 802.15.4 and threshold above ED [17].

2.5.5 PPDU Format

Figure 2.5 indicates the format of a PPDU. The PPDU packet format consists of the following elements:

- SHR, which contains information about synchronization and it is used to lock to frame by the receiver.
- PHR, which includes information about the frame length
- Variable payload length, which contains the MAC frame

Figure 2.5: *Format of the PPDU frame.*

2.6 MAC Sub-layer

The medium access control (MAC) sub-layer provides the transmission and reception of MAC frames through the physical channel. In addition to the data service, it enables management interface to physical medium. The responsibility of MAC sub-layer can be described as following:

- management of beacons
- Channel access control
- Frame validation
- GTS management
- Acknowledging of successful frame delivery
- Security services
- Association and disassociation

More details about physical and MAC layer can be found in [17].

2.6.1 Super-frame Structure

The super-frame is an optional structure used by the LR-WPAN. The structure of the super-frame is determined by PAN coordinator. Super-frame is confined between two successive beacon. Each beacon is divided into 16 equally sections named slots. As it mentioned earlier, since super-frame is an optional functionality, if a coordinator does not want to utilize super-frame it may stop beacon broadcasting. Moreover, beacon which is broadcasted in the beginning of the super-frame is applied for synchronization of associated nodes, PAN identification, and demonstration of super-frame structure. The super-frame includes active and inactive periods. The nodes should not communicate with the PAN coordinator during the inactive periods.

The active period is further divided in two parts: Contention Access Period (CAP) and Contention Free Period (CFP). Any device which want to communicate with other devices during CAP period should compete with other nodes using CSMA-CA algorithm to access medium. On the other hand, CFP period employs guaranteed time slots (GTS) which always come after CAP i.e. at the end of the active period. The PAN coordinator can assign up to seven GTSs and one GTS can occupy more than one slot.

The duration of active period of the super-frame can be adjusted by the values of *macBeaconOrder*, and *macSuperFrameOrder*. *macBeaconOrder* is a value defining

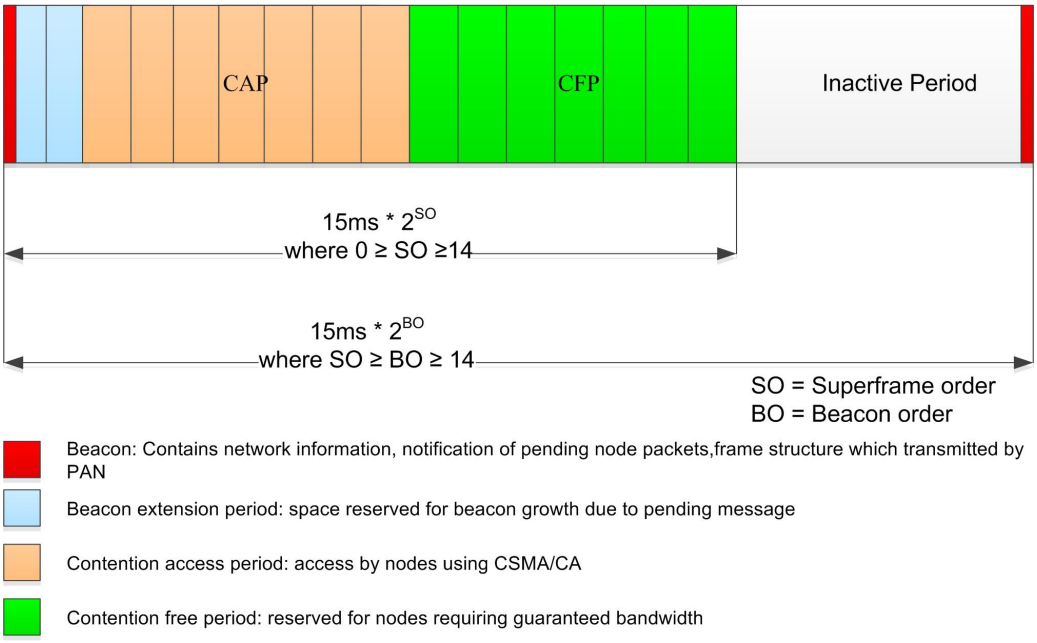


Figure 2.6: *Super-frame Structure.*

the length of the beacon interval (BI). Beacon interval is related to *macBeaconOrder* (BO) as below equation:

$$\begin{aligned} &BI = aBaseSuperFrameDuration * 2^{BO} \\ &where\, 0 \leq BO \leq 14 \end{aligned} \tag{2.2}$$

If $BO = 15$, then super-frame is ignored.

On the other hand, the duration of the active period of the super-frame is described by the value of *macSuperFrameOrder*. The super-frame duration (SD) is linked to *macSuperFrameOrder* by the following formula:

$$\begin{aligned} &SD = aBaseSuperFrameDuration * 2^{SO} \\ &where\, 0 \leq SO \leq 14 \end{aligned} \tag{2.3}$$

The beacon is broadcasted in the beginning of the first slot of the active period without performing CSMA-CA algorithm. The beacon is followed by the CAP. All frames excluding acknowledgments and all type of frames which followed after a data request command shall utilize the slotted CSMA-CA to access the medium. All frame transmissions in the CAP period should be accomplished before the ending of the CAP period, otherwise it will defer the frame transmission until the next CAP period. The structure of a super-frame is illustrated in Figure 2.6. The IFS is the required time for the physical layer to process a frame. In other words, the transmitted frame should wait for a limited amount of time called IFS. The length of the IFS depends on the frame size transmitted over the channel. If the frame

length is greater than *aMaxSIFSFrameSize* then frame shall be followed by a LIFS otherwise the SIFS shall be applied.

The CFP period should immediately start on a slot boundary after the CAP period. The CSMA-CA algorithm is not used in the CFP period. Moreover, the frame transmission shall be ensured that will be finished before the end of its GTS. If a PAN coordinator does not utilize the super-frame structure in non-beacon enabled network, the values of the *macSuperFrameOrder*, and *macBeaconOrder* should set to 15. The GTS and beacon broadcast are not permitted in the non-beacon enabled network. In addition, for transmitting any frame excluding acknowledgment, the unslotted CSMA-CA shall be applied [17].

2.6.2 Communication Mode

The MAC sub-layer provides two communication modes in the IEEE 802.15.4: Beacon enabled and non-beacon enabled mode. The non-beacon enabled mode is the simplest method to access the medium. In this mode, nodes obtain the access to medium by employing CSMA/CA algorithm without using the super-frame structure. It means that the nodes are not synchronized. The beacon enabled mode uses super-frame structure. In this mode, all devices are synchronized to beacon time interval and all activities including transmission and channel sensing are accomplished in the beginning of the slots. Using the CAP period of the super-frame, devices contend to get access by using CSMA/CA algorithm. In the contention free period, the access is granted to those nodes which are delay sensitive.

2.6.3 CSMA-CA Algorithm

The PAN coordinator will adopt the slotted CSMA-CA algorithm if it uses the super-frame structure. On the other hand, if the beacon cannot be located or cannot be broadcasted by the PAN coordinator, unslotted CSMA-CA is used in a non-beacon enabled network.

In slotted CSMA-CA, all nodes locate the backoff boundary by synchronizing to the beacon interval of the super-frame. Using this method, all the nodes of a PAN coordinator are synchronized. In the slotted CSMA-CA, when a device wishes to transmit a frame, it should locate the boundary of the following backoff period, however, in unslotted CSMA-CA, synchronization of nodes is not required. The duration of a backoff implemented by the CSMA-CA algorithm is called *aUnitBackoffPeriod*.

Each node should maintain three variables: NB, CW, and BE for each transmission attempt during the CSMA-CA algorithm. NB is the number of the CSMA-CA required to backoff for the ongoing transmission. NB is initialized to zero before the new transmission. BE is the Backoff Exponent to generate a random backoff

duration. CW is the Contention Window Length, defining the number of backoff periods that need to be clear of channel activity before the transmission can start. It is initialized to 2 before each transmission attempt and reseted to 2 when the medium is sensed busy.

Figure 2.7 presents the CSMA-CA algorithm including the slotted and unslotted cases. As figure shows, first of all algorithm determines which approach should be followed (step 1). In the slotted case, the values of NB, CW, and BE are maintained but the unslotted CSMA-CA just only tracks the value of NB and BE. In step 2, the MAC sub-layer should defer till the end of the backoff period which is in the range of $0 to 2^{BE} - 1$.

In the next phase (step 3), MAC requests from PHY layer to perform Clear Channel Assessment (CCA) on the backoff period boundary in slotted CSMA-CA mode. The MAC shall check if the time is enough for the remaining CSMA-CA algorithm including sending frames and acknowledgment before the CAP period, other wise it shall wait till the next CAP period to repeat the whole process. In the case of busy channel the MAC sub-layer shall increment NB and BE by one providing that NB shall not exceed the *macMaxCSMABackoff*. If NB surpasses the *macMaxCSMABackoff* value it will produce channel access failure, otherwise it shall

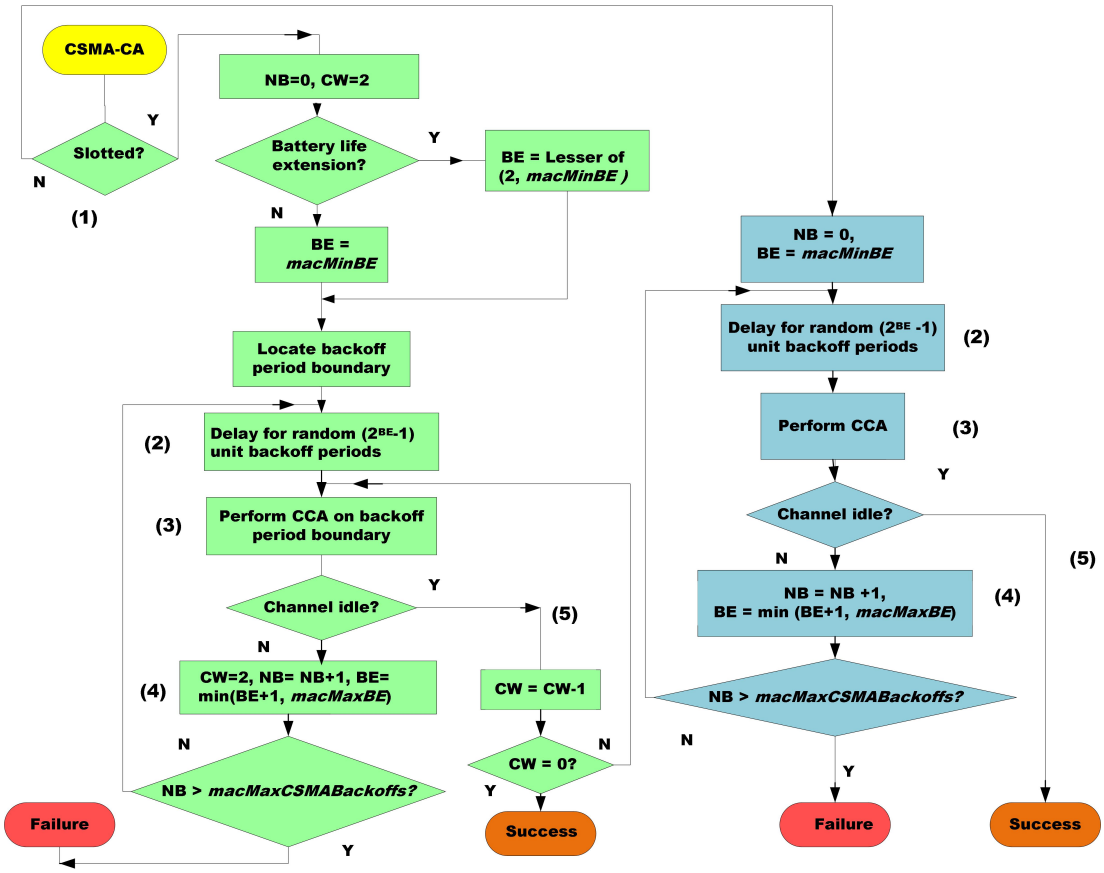


Figure 2.7: *The CSMA-CA Algorithm.*

return to step 2.

If channel is sensed to be idle, MAC shall check the CW value evaluating to 0, then it sends the frame but if the value of CW is not 0, the process commences from step 3. In unslotted CSMA-CA the frame is immediately transmitted after the medium is sensed to be idle without taking into account the backoff period boundary [17].

3. M2M APPLICATIONS REQUIREMENTS

3.1 Motivations

The world is ever connecting and the data exchange is rapidly increasing day by day. The revolution of the mobile network with the target of connecting whole people by the cell phone is slowing down. The revolution of the Internet era which was aimed to connect every computer to each another is slowing down as well. The new revolution is about to happen which is connecting things around us to create an Internet of Things (IoT) [18]. The term of Internet of Things (IoT) was introduced for the first time by Kevin Ashton in 1999 [19]. The IoT will change the concept of connectivity from anywhere, any time for everyone to connectivity for anything [20]. Not all objects connect in the first phase of the implementation but at least most important objects related to human health and safety will connect to lead the vision of the Internet of the Important Things (IoIT). This will cause to physical extension of current Internet [21].

Connecting devices and nodes is a great opportunity in instrumenting and interconnecting the physical world around us. IoT, along with opportunity, imposes serious challenges. The most important challenges are the interconnecting of a massive amount of objects with given restraints including power consumption, processing capabilities, memory and size [22].

Estimations and anticipations about number of connected objects are different. The WWRF (World Wireless Research Forum) anticipates that 1000 wireless devices will be available for each person by the year 2020 [23]. The ABI Research [30] predicts that there will be 225 million objects connected through the cellular links by the year 2014. The ETSI (European Telecommunications Standards Institute) estimates 50 billion communicating devices in the near future. Based on the Juniper's networks, around 428 million devices will be connected by the year 2014 [24]. Only time can tell the exact number of the objects but it is obvious that the number of wireless nodes per a person is increasing day by day and they will be uniquely identified and associated to the network with their known position and status. In addition, adding services and intelligence to this concept will expand the future Internet which consequently affects the future life and the environment [25].

Recently, *Machine-to-Machine* (M2M) communications have drawn many interests in academic and industrial environment because of the potential applications

of IoT and rapid development of wireless communication technology. The aim of M2M communications is to achieve ubiquitous communication between heterogeneous wireless devices and provide the data exchange between them [26]. M2M communications support a wide range of complicated and autonomous operations including advanced sensing, remote controlling, and monitoring technology [27].

The wireless Communication technology can be used for four distinct types of communication:

- Human-to-human communication
- Human-to-machine communication
- Machine-to-human communication
- Machine-to-machine communication

Human-to-human (H2H) and M2M communications have similar characteristics, however, there are some characteristics in M2M which are not supported in H2H. First of all, M2M communications shall support a large number of wireless nodes. On the other hand, the main traffic in M2M technology is the uplink traffic meaning that wireless devices send their data to an AP rather than receive the data. However, traffic in H2H is mainly down-link traffic due to higher user demand. The other issue is power consumption which should be as low as possible in M2M due to battery powered devices. Furthermore, M2M shall support various data transfer delay to be able to cover different applications and services [28]. There are also another characteristics belong to M2M technology including the small data transmission, priority alarm, and infrequent transmissions and so on [26].

3.1.1 M2M Architecture

The M2M architecture is comprised of three main interlinked domains:

- M2M device domain
- Communication network domain
- Application domain

The simple M2M architecture is depicted in Figure 3.1 and the elements of M2M architecture are tabulated in Table 3.1.

Capillary Networks

Capillary networks is a short range solutions in M2M technology which are mainly being standardized by various Standard Developing Organizations (SDOs) like IEEE,

IETF. Capillary network consists of the sensors, wireless nodes, communications and processing units which behave like the endpoints of the M2M applications. The interconnection between devices occurs via different PAN and LAN technologies in wireless or wire-line modes. These devices are composed of sensors, processors and radio transceivers. The most important technologies which enable WPAN networks are ZigBee, Bluetooth, and RFID. Wi-Fi technology over IEEE 802.11x is the dominant technology enabling WLAN network. The sponsors also play important role in forming M2M capillary networks used for coordination and transmission of the collected or aggregated data to the gateway. This smart nodes can form Bluetooth piconets, ZigBee networks or RFID networks [22],[29].

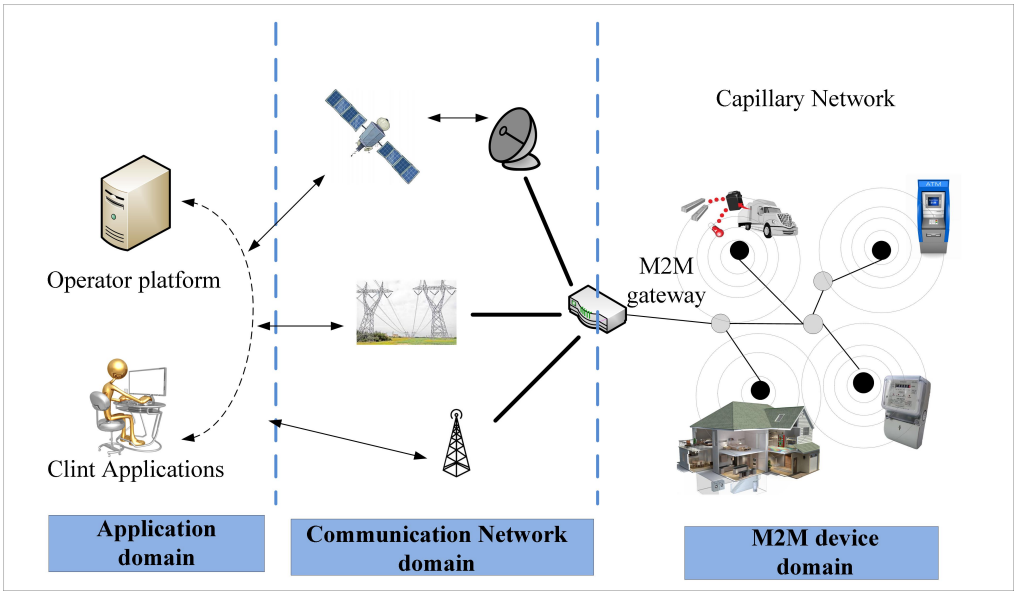


Figure 3.1: *Simple M2M Architecture [41].*

M2M Gateway

M2M gateway is a bridge between M2M device domain and network domain. This module provides control and localization services for collected data. For serving these domains, M2M gateway should support the standards in the both domains. It means that it should support ZigBee, Bluetooth, RFID, and Wi-Fi technologies from M2M device domain and cellular, satellite, power line communication (PLC) technologies from communication network domain. In addition, M2M gateway increases the traffic concentration to the core network [29].

M2M Backhaul

M2M backhaul is a bridge between the gateway and M2M applications which provides the network access for the M2M system. The M2M backhaul varies from

Table 3.1: *Elements of M2M architecture [29].*

Elements of M2M Architecture	Description
M2M Devices	• Device consists of sensors, processors, and transceiver capable of exchanging data autonomously. • Capillary Network is responsible for enabling connectivity within M2M devices and also between M2M devices and gateway. • Supporting these technologies: ZigBee, Bluetooth, RFID, Wi-Fi, SDR, UWB, M-BUS
M2M Gateway	• Interconnecting between backhaul networks and capillary networks.
M2M Backhaul	• Providing a communication link between gateway and M2M application. • Including these technologies: xDSL, PLC, Satellite, LTE, GERAN, UTRAN, W-LAN, and WiMAX.
Applications	• Consists of middleware executing the M2M business logic. It contains a software which enables analyzing data for the end user.

the wireless cellular solutions, which rely on wide coverage (for instance, GSM, UMTS, LTE, WiMAX) to wireless short-range solutions working on cheap and energy-efficient deployments (WiFi, Bluetooth, Zigbee, RFID) [34].

M2M Applications

It Contains the middleware layer where data passed to various application services and used by the specific business-processing engines.

3.2 M2M Use Cases

M2M has a wide variety of use cases and applications including home M2M network [31], home health care (Body area network), telematic and vehicles, telemetry, fleet management, service and maintenance, security and surveillance, and so many other applications. These use cases have identified by various standard organizations as well [32], [33]. Figure 3.2 shows the M2M applications in details and divides them in the same category. In the following, E-Health, smart grid and vehicular telematic are discussed in details as the most important use case of the M2M technology.

Figure 3.2: *M2M use cases [31].*

3.2.1 E-Health

E-health or M-Health is an emerging technology with the objective of improving the quality of patient care and reducing health care costs. The services encompass telemedicine improving care system using a fast, accurate, and real time report of the patient's physical condition, tele-conference between health care centers and medical groups, laboratories, and pharmacies to exchange medical data in order to reduce the costs.

The healthcare industry has allocated significant resources on developing telemedicine in both research and implementation in order to increase healthcare quality and reduce medical expenses. One of the most important outcome of this program is the patient tele-monitoring by using the bio-sensors to record patient's physical conditions and fitness indicators such as blood pressure, body temperature, heart rate and weight. These sensors transmit the collected data to an M2M device like patient cell phone. This device acts like a data aggregation which forwards them to M2M servers in the cloud. The servers collect and forward these data to medical center. It will trigger an alarm based on the patient's critical condition to perform an appropriate action in order to cure patient in the emergency cases [31].

3.2.2 Smart Grid

Smart grid is an intelligent system which integrates utility systems (such as electricity, gas, or water), communication technologies and delivery infrastructures. This

mixture makes the system autonomous in terms of monitoring and control. It also enables demand response functionality and improves the efficiency of resource utilization. The main outcomes of smart grid are smart metering, intelligent distributed network, equipment diagnostics, and monitoring and control.

The M2M smart meters send the usage data of customers using short range communication technologies to M2M servers. M2M servers using 3G or 4G network collect data and send them to core network. The M2M aggregation data collects information from many smart meters by using different short range wireless technologies. These technologies are mainly Wi-Fi, ZigBee, or 3G/4G [31], [35].

3.2.3 Asset Tracking

Asset tracking systems give many opportunities including parameter monitoring, remote controlling and movement surveillance of the asset to owners or users of equipments. The assets or cargoes specially the more valuable ones are required to be tracked using M2M equipments particularly in places where physical access is difficult. In addition, in some occasions, protecting the asset against thieves by human recourses are quite challenging task which needs M2M devices to be performed more preciously and all the time. On the other hand, in the case of high mobility assets, M2M technology will ease the monitoring and remote controlling by minimum costs [36].

3.3 M2M Communication Requirements

M2M communication is sort of communication between two or more machines without direct intervention of the human beings. The M2M services are designed to perform in a autonomous and automatic manner between entities. Achieving this objective, some requirements shall be fulfilled in M2M communications. Some of the requirements to enable consistent, cost effective communications for a wide variety of applications are documented in the following list.

- **Scalability**:
  One of the biggest factors that service providers will need to prepare for is scalability. As more and more devices and systems connect to each other not just a few devices but potentially billions of them, the network will need to be able to scale to meet demand.

- **Abstraction of technologies heterogeneity**:
  The M2M gateway should be able to interface to wide variety of M2M applications using different wireless technologies.

- **Mobility**:
  In the case that underlying network provides seamless mobility and roaming, the M2M system should be compatible with such a mechanism.

- **Support of multiple M2M Applications** The M2M system should support multiple applications due to heterogeneity of the wireless nodes and their applications. This mechanism should support the following principles:

  1) The list of the registered M2M applications shall be maintained.
  2) The information related to the registered application should be maintained.
  3) The newly registered M2M application should be subscribed, and authorized for the information exchange.

There are other requirements for the M2M communications as well which are concisely mentioned as following:

- Message Delivery for sleeping devices
- Radio transmission activity indication and control
- Message transmission scheduling
- Communication with devices behind a M2M gateway
- Communication failure notification
- M2M Service Capabilities discovery and registration
- Communications integrity
- Device/Gateway integrity check
- Continuous connectivity
- Device/Gateway failure robustness
- Location reporting support

More details about the M2M applications requirements can be found in [37].

4. ZIGBEE COMPARISON WITH OTHER M2M ENABLING TECHNOLOGIES

Bluetooth (based on IEEE 802.15.3), RFID (over ISO 18000) and Wi-Fi (based on IEEE 802.11) are three technologies aimed for short range wireless communications with low power consumption. These technologies are characterized by the similar requirements needed in Internet of Things (IoT) [23], [20],[19] and M2M [38],[39],[40] applications, therefore, these technologies are possible candidate for IoT and M2M use cases in near future. These technologies are introduced and their main characteristics are discussed in this chapter. Moreover, the comparison study of the aforementioned technologies with ZigBee technology is investigated in the end of the chapter.

4.1 Bluetooth

4.1.1 Overview

The explosive growing of hand-held devices are rapidly changing our lives. Many personal devices such as cell phones, laptops, palmtops are surrounding human beings in the new millennium. In most of the cases, these devices have no compatible data communication interfaces or if they do, the connection between devices are via problematic cable connection. The idea of removing the extra connection cables was invented by Ericsson company in 1994 which was an alternative to remove cable connections of mobile accessories. This technology named Bluetooth was a low power, low range and low cost radio interface solution for that problem. In 1998 five major companies including Nokia, Ericsson, IBM, Intel and Toshiba formed the Bluetooth Special Interest Group (SIG) to develop the technology and broaden the market which defined the initial specification. At the end, the IEEE 802.15.1 standard, which Bluetooth is based on it, was published in 2002 [42]. The main features of the Bluetooth are:

- Minimal hardware dimensions.
- Low cost Bluetooth components (Low cost technology).
- Low power consumption.

- Short range.

The low cost and small size of the Bluetooth enable this technology to be integrated into many portable devices such as smart phones, PDAs and laptops. On the other hand, low power consumption aspect of the Bluetooth allows the devices to save more energy to prolong their battery life. This characteristic of the Bluetooth is significantly important since most of the devices are limited from energy point of view.

4.1.2 Bluetooth Networking

Bluetooth enables the communications between device by establishing one device as a master and other devices as slaves. No difference between devices to be chosen as a master. In other words, each device is able to act as a master device. This property makes this technology to behave as an ad-hoc network. Master device defines the frequency hopping pattern according to its address [43]. Two different topologies are defined in Bluetooth technology to form a network: piconet and scatternet.

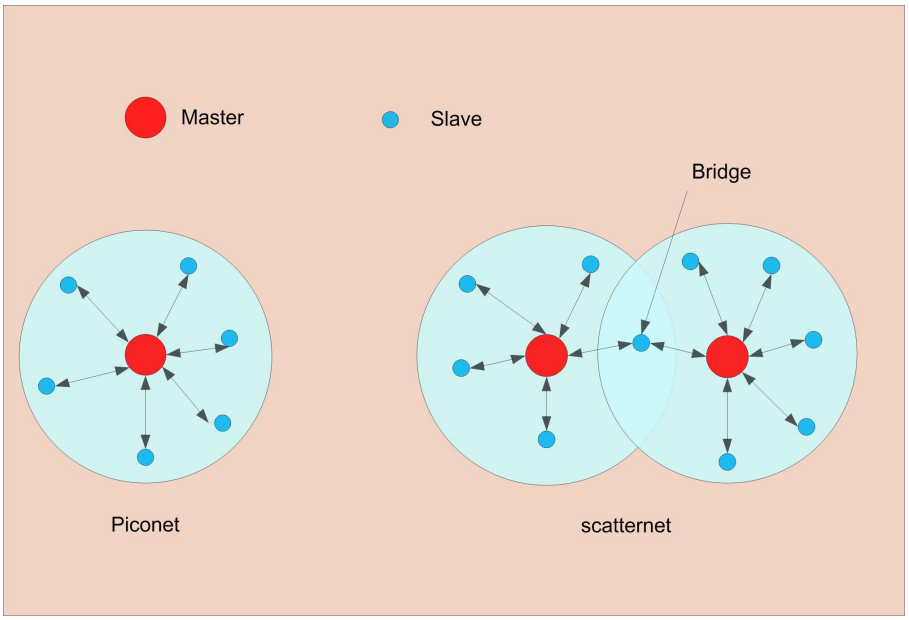


Figure 4.1: *Piconet (left) and scatternet (right).*

Piconet Piconet is an ad-hoc network in which all the devices have the same synchronized frequency hopping. This network independently works only with one master and all other devices obey the master. The master device can be replaced by another slave devices in the case of their request. One of the important functionality of the master is allocating fair bandwidth to each slave device. This topology can support up to 8 active devices and 248 parked

devices along with enormous standby devices. Figure 4.1 refers to these topologies. The left hand side topology refers to piconet and right hand one presents the scatternet topology supported by Bluetooth technology[43].

Scatternet Scatternet is a topology formed by the overlapped piconet networks. A master can leave one piconet and jump to another adjacent piconet or it can simultaneously be a slave device in another piconet network while it is a master in its own piconet network. In addition, the entire devices use the same frequency range allocated to Bluetooth technology but each piconet network employs different frequency hopping scheme to avoid occurring undesirable interference. This topology increases the optimal use of the available bandwidth.

Figure 4.2: *Typical Bluetooth products.*

4.1.3 Bluetooth Profile Specification

The Bluetooth Special Interest Group (SIG) has specified Bluetooth profile to fulfill the desired functions in the usage model. The profile defines the stacks and controller settings along with required procedures and feathers needed for interworking among devices. In other words, each profile specifies particular messages from the Bluetooth specifications. The related devices must support at least one profile. Therefore, devices with the same profile can communicate with each other. For instance, both cellular phone and headset are able to communicate via Bluetooth since they support the headset profile[44].

Table 4.1: *Profiles specified in Bluetooth specifications.*

Profile	Description
Generic access	Generic procedures related to discovery and link management of connecting Bluetooth devices.
Service discovery	To discover available services and in the range devices.
Cordless telephony	To enable using the Bluetooth enabled devices as a cordless telephone.
Serial port	To set up emulated serial cable connections using RFCOMM between two peer devices.
Headset	To enable audio communications between the Bluetooth equipped devices.
Intercom	Requirements to support of the intercom functionality among the "3-in-1" phone use cases.
Dial-up	To enable dial-up Internet connection.
Fax	To support communication between Bluetooth devices implementing fax services.
LAN access	To enable local area network over PPP.
Object exchange	Requirements for Bluetooth devices to support Object exchange usage model.
Object push	Requirements for Bluetooth devices to support object push usage model.
File transfer	To support the file transferring functionality.
Synchronization	To support synchronization usage model.

The profile is meant to reduce the interoperability between different devices from different vendors. Table 4.1 presents some of the prevalent profiles which are used by the different Bluetooth devices. The wide area of the applications is also shown in Figure 4.2.

4.1.4 Technical Characteristics of Bluetooth

The technical characteristics of the Bluetooth are described in this section. These characteristics are according to Bluetooth objectives such as low cost, low power consumption and high data rate which are relatively fulfilled by this technology. Some of the important characteristics of the Bluetooth are listed in Table 4.2.

As Table 4.2 indicates, the aggregate data rate is 1 Mbps for the approximate range of 10 meters. The range depends on the class of the devices and, therefore, on the type of the transmission power. Hence it leads to three class of devices:

1. Class 1: This class is designed to support high range applications such as Bluetooth access point in the approximate range of 100 meters and with power of 20 dBm (100 mW).

Table 4.2: *Technical characteristics of the Bluetooth[44],[42].*

Characteristics	Bluetooth
Average range	10 meters
Operating frequency	2.4 GHz ISM
Data rate	1 Mbps
Network Topology	Adh oc piconets
Number of devices per network	8

2. Class 2: This class is meant for moderate range (10 meters) devices such as PC peripheral accessories with power of 4 dBm (2.5 mW).

3. Class 3: This class works for very low power devices operating in the range of 1 meter with power of 0 dBm (1mW) [45],[44].

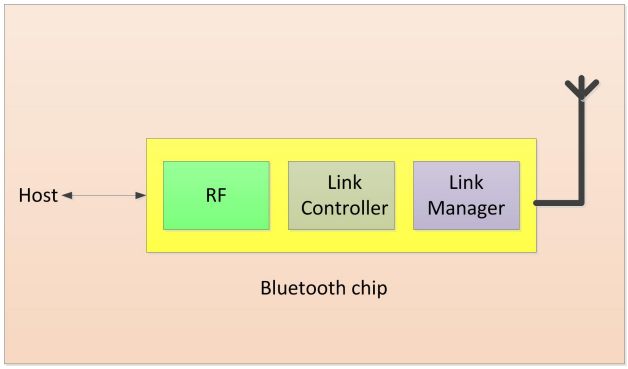


Figure 4.3: *Bluetooth chip.*

Figure 4.3 shows the typical Bluetooth chip which consists of several modules such as radio front end, link controller, and link management. The Bluetooth Link controller executes the baseband protocols and low level link functions. On the other hand, link manager accomplishes the link set-up management and control protocols. More details about the aforementioned modules are discussed in the following sections.

4.1.5 Protocol Stack of Bluetooth

A protocol stack is a prescribed hierarchical software layers, starting from the application layer at the top to link layer at the bottom, based on the specified standard which enables devices to communicate with each other. Figure 4.4 presents the Bluetooth protocol stack. In the following, some of the most important parts of the protocol are concisely described.

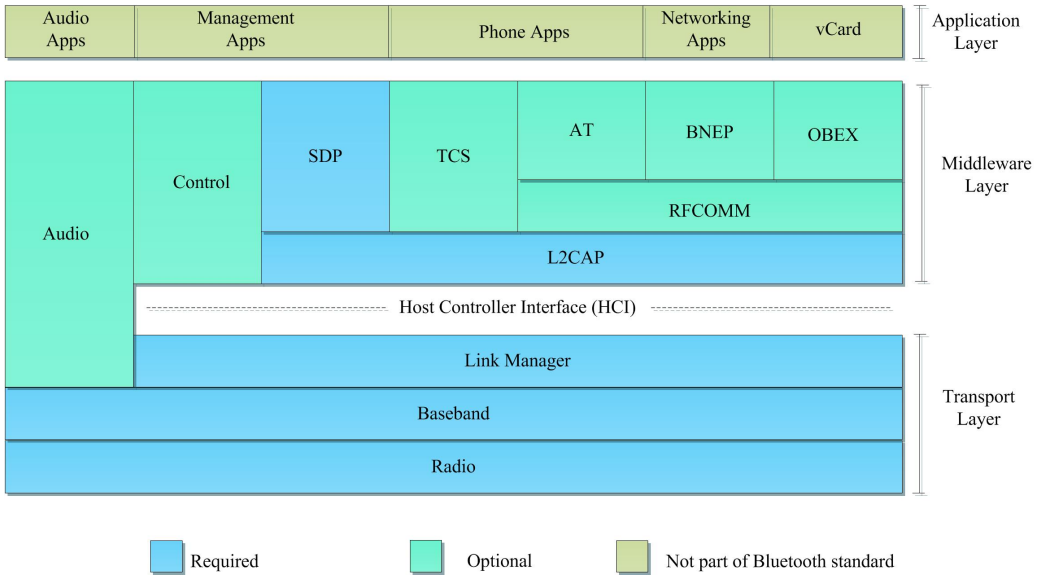


Figure 4.4: *Bluetooth protocol stack.*

Radio layer Bluetooth technology communicates in the radio level similar to other wireless technologies. Data is transmitted in a bit format over radio frequency. The radio layer is responsible for this function. Bluetooth radio layer applies Gaussian frequency shift keying (GFSK) to modulate data and transceiver it over available channels. As it already mentioned, the Bluetooth transceivers come in three power classes. The radio frequency assigned to Bluetooth is 2.4 GHz ISM band. Most of the countries use the frequency band 2400 - 2483.5 MHz, although some countries have national limitation in this band which in turn they use another frequency bands. The aforementioned band is divided into 79 channels. Each channel is further divided into the time slots of 625 μs length, therefore, 1600 slots exist per second which create 1600 hops per second. The time slots are numbered based on the Bluetooth clock of the piconet master. The numbers are cyclic of the period of 2^{27}. In other words, the range of these numbers is from 0 to $2^{27} - 1$. The time slots enable packet transmission between master and slaves. When master and slaves alternatively communicate together, TDD scheme is employed to allow them to access to the channel. In addition, master shall transmits in even number slots while slaves transmit their packet in the odd number slots.

Bluetooth baseband layer The baseband layer is responsible for the frequency hopping functionality in order to interference cancellation, medium access control, and data encapsulation and decapsulation in the form of the packet. This layer uses the time division duplex (TDD) scheme to overcome concurrent communication of transmitter and receiver. In addition to aforementioned functionalities, baseband layer manages link and channel control along the flow and congestion control. The

error correction is another task which is done in this layer.

Link protocols As Figure 4.4 shows, Link Manager Protocol (LMP) and Logical Link Control and Adaptation Protocol (L2CAP) are responsible for link set-up and control. These protocols are necessary to manage device pairing, synchronization, quality of service, and encryption. Bluetooth devices should exchange several control messages to configure and manage the baseband connection. The definition of these messages is part of LMP. On the other hand, LPM performs Link set-up, authentication, encryption, power control and link configuration. The L2CAP is responsible for QoS support, protocol multiplexing, and reassembly of the PDU of the upper layer. Furthermore, it provides a connection-oriented and connectionless data services to the higher layers. The Service Discovery protocol (SDP) discovers services available in the proximity and defines the characteristics of the services.

4.2 RFID

Radio Frequency Identification (RFID) is a wireless technology which allows for short range and remote capturing data from a low cost and compact data source. This data may provide identification, location information, or specific knowledge about products like the date of production or expiry. More details are presented in the following sections about the RFID system.

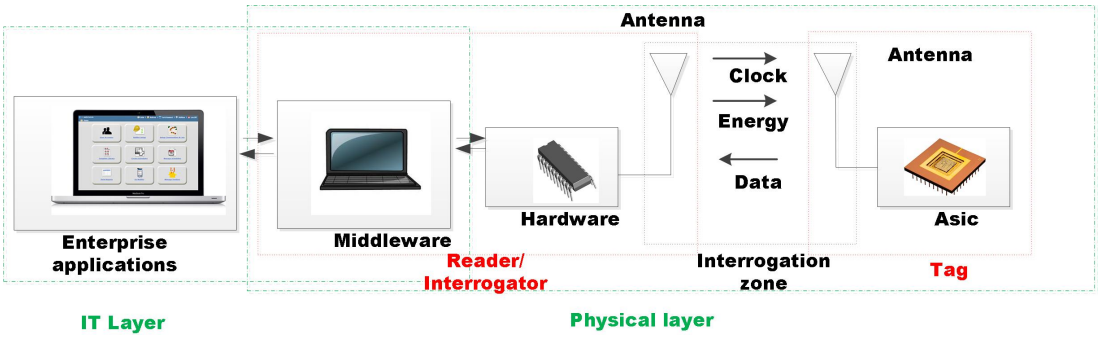


Figure 4.5: *Overview of generic RFID system [46].*

4.2.1 Overview of the RFID System

The RFID system comprises of a device to access data known as reader (interrogator) and a data-carrying transponder so called tag. Tags are attached to items which are monitored or positioned or carried by individuals. Readers collect data from the tag attached to an asset being passed from a particular location [47]. Figure 4.5 shows the generic overview of a typical RFID system. System is divided to IT layer and physical layer. As the figure shows the physical layer consists of Tag, reader/interrogator and Interrogation zone (IZ) [46].

Tag

Tags has the same functionality as optical bar-cods which are meant to identify the attached objects and items. Tags which also called transponder, consists of two main parts: IC cheap and antenna. IC cheaps are able to store data and process them and antennas can transmit the data whenever it is in the interrogator zone. There are three main tags from power supply point of view: active, semi passive, and passive tags. Active tags have a source of energy like battery, whereas passive tags require no power sources. Hence, active tags work in higher operational range compared to passive tags. But this attribute comes in trade of higher price for active tags. Passive tags come in different shapes and packages due to lacking of power source. These tags operate in LF (low frequency), HF (high frequency), or VHF (very high frequency) band. On the other hand, active and passive tags are more expensive and less resistant to mechanical stress and more problematic in the high temperature environment [48].

Reader

Readers in RFID are similar to the scanners in optical bar-code systems. Readers have three main functions:

- Support energy for the tag.
- Provide a carrier signal.
- Decode and detect the modulated signal [49].

The reader is able to be read or read/write a device that uses an antenna to send a radio frequency electromagnetic wave to the tag. Both power and data can be sent. Once the tag is energized it will either send its stored data or be updated with new data depending on the wish of the user. The reader is comprised of antenna and interrogator circuitry. The circuitry is like a intermediate module between antenna and IT layer. It sends data via readers antenna and receives data and transfers it to higher layer for further process [46].

Interrogation Zone

Interrogation zone is an area in which reader and tag interact to each other to exchange data. This zone consists of everything in the vicinity of the tags where electromagnetic waves travel between them [46].

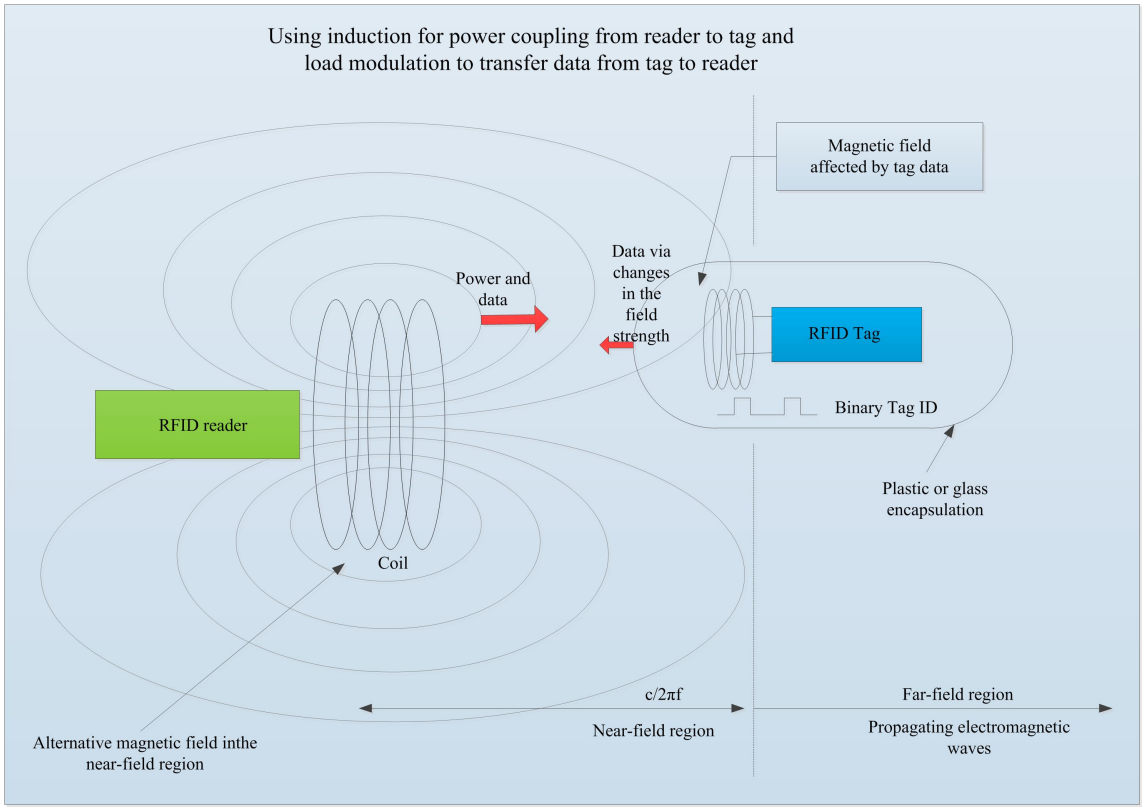


Figure 4.6: *Near-filed power/communication mechanism for RFID system [50].*

4.2.2 Near-field RFID

The basis of the near-field coupling between reader and tag is Faraday principle of magnetic induction. Passing a large alternating current through a coil in the reader produces the alternating magnetic field in the vicinity of the coil. By using another small coil in the tag located in the range of this magnetic field leads to an alternating voltage. This voltage is rectified by using a rectifier and is stored in a capacitor which provides enough power to energize the tag chip. Figure 4.6 shows the near-field mechanism of the RFID system. Tag sends its data back to reader using *Load modulation*. The induction current flown in the tag coil itself produces small magnetic field which will oppose to reader's magnetic field. The reader coil will detect this small changes as an increased current. This current is proportional to the data which applied to tag's coil. Employing near-field mechanism in passive tags is very straightforward but it has some drawbacks as well. The range of coverage in magnetic induction can be approximated by $c/2\pi f$, where c is a constant (speed of light) and f is the frequency. As operating frequency increases, the range between tag and reader decreases. On the other hand, magnetic filed drops off as a factor of $1/r^3$, where r is the distance between the reader and tag [50].

4.2.3 Far-field RFID

Tag based on far-field communication captures *electromagnetic* (EM) waves transmitted from the dipole antenna of the reader. Tag absorbs the energy as an alternative potential difference which appears across its dipole antenna. A simple rectifier like a diode rectifies the potential. The diode is connected to a capacitor which accumulates the energy required for powering the tag circuitry. Unlike the near-field tags which use *load modulation* to send data back to readers, far-field tags employ *back scattering* to transfer data beck to readers. The antenna will absorb the most energy in the current frequency in the case of designing the appropriate size of the antenna. However, if an impedance mismatch occurs antenna will reflect some of the energy toward reader. By adjusting the impedance mismatch and using a transistor the amount of back scattering waves can be controlled.

The range of RFID system based on the far-filed mechanism is limited to the amount of the energy receives to the antenna of the tag. The back scattering waves received in readers are resulted in two successive attenuations. The attenuation occurs when EM travels from reader to tag and the second one when it radiates from the tag to the reader. This attenuation is proportional to $1/r^4$, where r is the distance between reader and tag. Hence, the energy of the back scattered wave is so small. But thanks to improvement in semiconductor industry the amount of energy required for this circuits is ever decreasing [50].

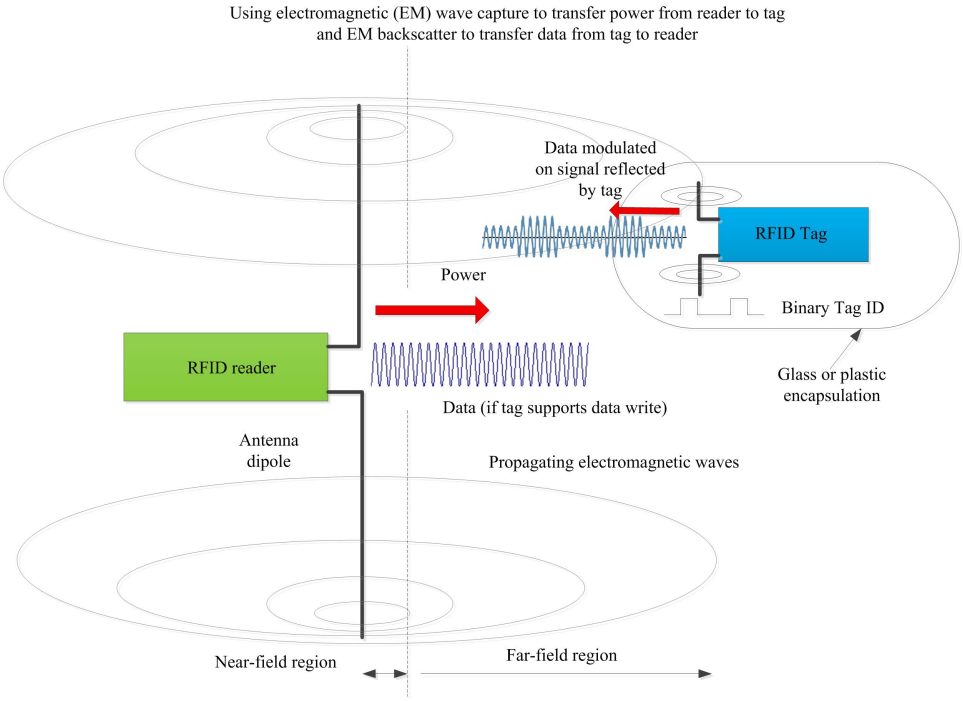


Figure 4.7: *Far-filed power/communication mechanism for RFID system [50].*

4.3 Wi-Fi

Wi-Fi is the commercial name for the Wireless Local Area Network (WLAN) based on IEEE 802.11 standard which officially released in 1997 [51]. WLAN was specifically created to operate as a wireless Ethernet. This technology provides wireless connectivity for end users in local area network. Internet access is provided at broadband speeds through Wi-Fi to an access point (AP) or in ad-hoc mode.

The IEEE Standard Association is responsible for developing the IEEE 802.11™. The main tasks of this organization are designing, developing, and standardizing the new technologies. The objective of the IEEE 802.11™ is providing the wireless connectivity between the stations within the wireless local area network.

IEEE 802.11 standard defines two ways of transmission of signal through the air. These two ways can be implemented either optical or radio technology for the WLANs. Firstly, the original standard defined 1 Mbps and 2 Mbps rates by using Frequency Hopping Spread Spectrum (FHSS) and Direst Sequence Spread Spectrum (DSSS) as the spread spectrum modulation. The main issue of the 802.11 was low data rate specially in business environment. To increase the data rate, IEEE 802.11 group developed new amendments of the current standard. In the following, some of the most important amendments of IEEE 802.11 family are described:

- IEEE 802.11a
- IEEE 802.11b
- IEEE 802.11g
- IEEE 802.11n
- IEEE 802.11ac
- IEEE 802.11ah

Table 4.3 shows the modulations used in IEEE 802.11 standard family.

IEEE 802.11a

IEEE standard 802.11a has been released in 1999 operating in the 5 GHZ spectrum. The 802.11a standard was designed to improve the data-rate using the higher frequency band and efficient modulation technique (OFDM). The following sub-carrier modulations are utilized by this standard: Binary Phase Shift Keying (BPSK) modulation, Quadrature Phase Shift Keying (QPSK), 16-QAM (Quadrature Amplitude Modulation) and 64-QAM. The main drawback of this standard is having the lower coverage range due to higher propagation loss in the higher frequency bands.

IEEE 802.11b

The 802.11b standard improves the data-rate up to 11 Mbps in the 2.4 GHz unlicensed spectrum using the complementary code keying (CCK) modulation. This modulation makes efficient use of the radio spectrum.

IEEE 802.11g

The IEEE 802.11g standard has been ratified in 2003. The 802.11g provides higher bandwidth up to 54 Mbps. This standard is backward compatible with the previous released standards. This standard utilizes the efficient modulation technique like OFDM to improve the performance of the standard in 2.4 GHz ISM band.

IEEE 802.11n

IEEE 802.11n published in 2009 increases the data-rate up to 600 Mbps. This standard improves the performance by adding multiple-input multiple-output (MIMO) antennas. IEEE 802.11n operates in both 2.4 GHz and 5 GHz frequency bands which the latter one is optional. IEEE 802.11n utilizes orthogonal frequency division multiplexing (OFDM) method like 802.11a and 802.11g, but it updates many features of OFDM to obtain higher data rate [62].

IEEE 802.11ac

IEEE 802.11ac is meant to produce very high throughput (VHT) connection for WLAN. The operating frequency band for this standard is on 5 GHz spectrum. Achieving very high throughput up to 6 Gbps is possible by utilizing efficient OFDM modulation technique, increasing number of MIMO antennas and high density modulation (256-QAM). In addition, IEEE 802.11ac has many improvement in the physical and MAC layers compared to the IEEE 802.11n [64].

IEEE 802.11ah

The IEEE 802.11ah standard is on final stage of development. It can be one of the candidate standards for IoT and M2M applications. This standard is being developed by gathering proposals by the IEEE 802.11ah task group and it is expected to be published by the year 2014. The IEEE 802.11ah will operate in Sub-1 GHz unlicensed frequency band enabling the data transmission for the bursty traffics [80].

The operating bands for this standard will be one or more from the following bands: 863-868.6 MHz (Europe), 950.8 MHz -957.6 MHz (Japan), 314-316 MHz, 430-432 MHz, 433.00-434.79 MHz (China), 917-923.5 MHz (Korea) and 902- 928 MHz (USA). The main benefit of utilizing the above mentioned spectrum is the

Table 4.3: *Modulation in IEEE 802.11x*

Standard	802.11	802.11b	802.11a	802.11g	802.11n	802.11ac/ah
Modulation	FHSS, DSSS	DSSS	OFDM	OFDM, DSSS	OFDM	OFDM

improvement of the coverage area for the IoT applications which increases the energy efficiency. In addition, by using simplified hardware-structure for the IoT device components, achieving low cost technology is also possible. All in all, these attributes make this band interesting for the IoT and M2M applications in near future. The main functional requirements for IEEE 802.11ah [80], [81] are the following:

- The provided coverage area up to 1000 m.
- Data exchange of 100 kbps and higher.
- maintaining the IEEE 802.11 WLAN user experience for fixed, outdoor, point to multi-point applications.

The desired coverage area is relatively high compared to the legacy standards but instead, the required data-rate is quite small.

4.3.1 IEEE 802.11 Architecture

The IEEE 802.11 standard consists of three mode: infrastructure mode, ad-hoc mode, and mesh mode.

Infrastructure mode is a cellular structure which has at least one AP. The system is divided into cells called Basic Service Set (BSS). Each cell consists of a set of the fixed or mobile stations which are controlled by a Base Station or AP. All the stations share the same wireless medium within a cell and compete to obtain the access to the medium. The operating range between stations are limited to their power and propagation conditions like indoor and outdoor environments. The coverage of the wireless area can be expanded by overlapping multiple BBSs. Each AP in BSS connects to a distributed system (DS) which allows communication between cells. The extended version of network built with multiple BSSs is Extended Service Set ESS (See Figure 4.8) [52], [53].

Stations in ad-hoc mode communicate without any AP. This mode is called independent basic service set (IBBS) as well. The formation of the network is possible without any pre-planning or using infrastructure. Figure 4.8 shows IBSS and ESS configurations of Wi-Fi networks [52], [53].

The third type of network configuration is mesh mode which is a combination version of infrastructure mode and ad-hoc mode [52].

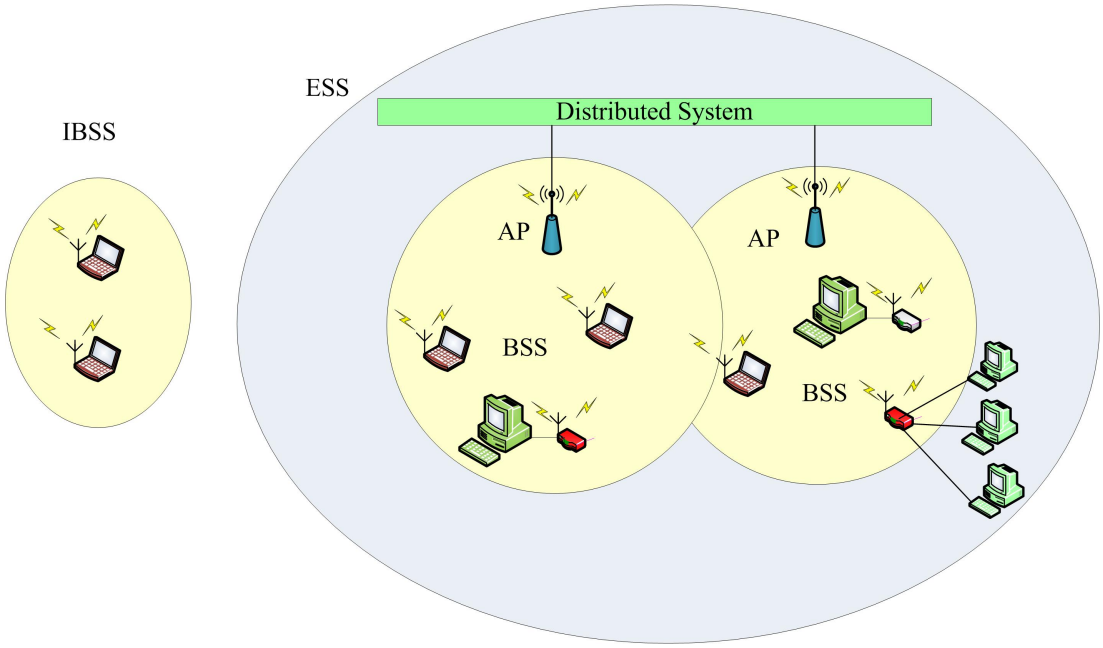


Figure 4.8: *IBSS and ESS configurations of Wi-Fi networks [53].*

4.3.2 Physical Layer

The IEEE 802.11 employs several modulation techniques in physical layer which are: Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS), and Orthogonal Frequency Division Multiplexing (OFDM). Table 4.3 shows the modulation techniques used in IEEE 802.11.

Frequency Hopping Spread Spectrum (FHSS) is a method for transmitting a radio signal by rapidly changing the operating frequency from a set of frequencies. This frequencies are changed based on a pseudo-random scheme which is known to both transmitter and receiver [55], [56].

Direct Sequence Spread spectrum (DSSS) is a technique to spread the data bearing signal over the whole bandwidth using a higher bit rate sequence called *chipping code*. The chipping code is a redundant bit pattern for each transmitted data which makes transmitted signal very resistant against interference. If some errors happen during transmission, data will be corrected in the received signal by using the redundancy [57], [58].

Orthogonal Frequency Division Multiplexing (OFDM) is a special case of multicarrier transmission where data stream is transmitted over lower bit rate sub-carriers. This method can be used as a modulation or multiplexing. The reason for using OFDM technique is the robustness against frequency selective fading and narrow-band interferences [59], [60].

4.3.3 MAC Sub-layer

MAC layer of the IEEE 802.11 provides two main access mechanisms: Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF is a distributed and random access for the stations which is used for asynchronous data transmission. This algorithm should be implemented in all stations which work in this mode. PCF is an optional mode which is based on polling controlled by the AP. PCF is suitable for real time traffics such as audio and video as well as asynchronous traffics. In the case of using both DCF and PCF, standard defines a hybrid method so called Hybrid Coordination Function. In this method, the wireless medium is divided into super-frames. Each super-frame is comprised of Contention Free Period (CFP) which represents PCF method and Contention Access period (CAP) which represents DCF mechanism [61].

In the DCF protocol, stations obtain access to wireless medium using *basic access method* or *four-way handshaking method* with extra *Request to Send* (RTS) and *Clear to Send* (CTS) packets. The station having a packet to send senses the channel. If the channel is busy it will wait until channel is idle again. The station defers the process for *Distributed interframe space* (DIFS) then it chooses the backoff interval between $[0 - CW - 1]$ based on the uniform distribution. The contention window for transmitting a packet for the first time is CW_{Min}. It is doubled in the case of failure until it reaches maximum value CW_{Max} and it stays at CW_{Max}. backoff decreases by one with each timeslot and the counter is stopped when the channel is sensed busy. The timeslot duration is the minimum time required for a station to detect an idle channel plus the time required switching from listening mode to transmitting mode. The counter restarts to decrement after channel sensed idle after a DIFS. When bachoff counter reaches zero, the packet is transmitted. If the receiver successfully receives the entire packet an *Acknowledgment* ACK packet after a short interframe space (SIFS) period is transmitted to the sender. If transmitter does not detect the ACK packet within SIFS time, the transmission process is assumed to be unsuccessful and it will restart it again. If the process is successful the value of CW resets to CW_{Min} [63], [65].

In four-way handshaking scheme, each station employs additional RTS/CTS packets compared to basic access scheme. When backoff counter reaches zero, transmitter initializes an RTS to receiver and in reply, receiver responds with an CTS to the transmitter. The Packet is immediately transmitted when CTS is received by the transmitter. Using RTS and CTS resolves the hidden node problem in wireless communication [65]. Basic access and RTS/CTS method is presented in Figure 4.9.

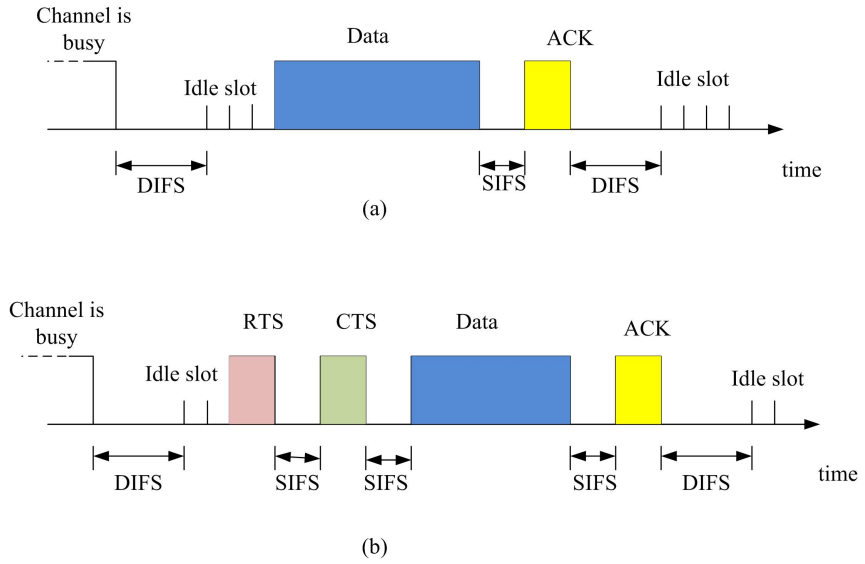


Figure 4.9: *The IEEE 802.11 access methods: (a) Basic access method. (b) Four-way handshaking access method.*

4.4 ZigBee Comparison with Bluetooth, RFID, and Wi-Fi

4.4.1 RF Channels and Bandwidth

Table 4.4 presents some of the main differences between Zigbee and other technologies. As Table 4.4 shows, these technologies operate in wide range of frequency bands. For instance, RFID operates in 125 KHz (LF), 13 MHz (HF), 900 MHz (UHF), and 2.45 GHz (Microwave) [66]. ZigBee operates in 868/915 MHz and 2.4 GHz and Wi-Fi works in 2.4 GHz and 5 GHz. Bluetooth only operates in 2.4 GHz band. It can be observed that all technologies utilize 2.4 GHz frequency band known as ISM (industrial, scientific, and medical) which is unlicensed in most countries. Bluetooth employs frequency hopping (FHSS) with 79 channels and 1 MHz bandwidth, while ZigBee utilizes direct sequence spread spectrum (DSSS) with 16 channels and 2 MHz bandwidth. Wi-Fi uses DSSS in 802.11 standard, complementary code keying (CCK) in 802.11b , or OFDM modulation in 802.1 1a/g/n with 14 RF channels and 22 MHz bandwidth. RFID systems using ISO18000-6 standards applies FHSS for the communication between tag and reader [67]. This means that an RFID reader may hop between channels within the operating band of frequencies in a pseudo-random manner.

4.4.2 Datarate and Modulation

ZigBee is designed for the low rate and low consumption applications such as wireless sensors which do not require high rates standards. The ZigBee supported by the IEEE 802.15.4 standard has a rate of 250 kbps in 2.4 GHz frequency band. However,

data rate of 20 kbps in 868 MHz band and 40 kbps in 915 MHz band are used in some countries as well. This technology uses the following modulations: BPSK, ASK and OQPSK.

RFID system operates in different frequency bands from LF to microwave band and tags work in passive, semi-passive and active class so that different data rates are available for this technology in the range of 1 kbps to 200 kbps. ASK, PSK and FSK are the digital modulations which RFID system employs them.

Bluetooth using GFSK modulation operates with 1 Mbps and it has fairly high data rate in wireless personal area network. In contrast, Wi-Fi has a wide range of data rates due to different allocated bandwidths and different supported protocols. Therefore, the range of the data rate and occupied bandwidth is so dynamic in Wi-Fi technology. For instance, IEEE 802.11b operates in 1 Mbps data rate while the IEEE 802.11ac ,which is the newest Wi-Fi protocol, can acheive a data rate of 1 Gbps [68]. Different modulations are applied in Wi-Fi technologies including BPSK, QPSK, OFDM, CCK, M-QAM.

4.4.3 Network Size and Range

The maximum number of nodes per network for Bluetooth is 8 nodes which includes 7 slaves and one master. This number is 2007 nodes for a structured Wi-Fi BSS. In this regard, ZigBee can have more than 65000 nodes in a star network. These technologies can be extended to more complicated networks, for instance, ZigBee can be extended to cluster tree or mesh network, Wi-Fi to ESS and Bluetooth to scatternet network [69] [70]. Refer to Table 4.5 for comparison study of ZigBee, Wi-Fi and Bluetooth.

As Table 4.4 presents, ZigBee has a wide variety of coverage range. This range extends from 10 meters to 100 meters depending on the type of the sensors and class of transmission. In contrast, the range of Bluetooth is less than ZigBee and it is from 10 meters to 30 meters. This shows that Bluetooth fairly has less coverage range than ZigBee technology. In RFID technology, the variety of coverage is even more dynamic than the ZigBee technology. The typical coverage range is 6 meters for passive tags and 120 meters for the active tags. Wi-Fi relatively has large coverage range of 100 meters since it is designed for the local area network [69].

4.4.4 Transmission Power

As Table 4.4 shows, ZigBee has the lowest transmission power among the other technologies . The range of the transmission power for the ZigBee technology is between -25 dBm to 0 dBm. In RFID technology, the transmit power depends on the type of the tag. In semi-active and active tags, the range of the transmission

power is changing between 1 mW to 4 W [66]. The transmit power in Bluetooth technology is in the range of 1 mW to 10 mW and the Wi-Fi has the transmission power of 100 mW. However, in IEEE 802.11ah technology ,which is meant for the IoT and M2M applications, the typical transmission power is of 1 mW.

Table 4.4: *Comparative Study of ZigBee Technology with other M2M enabling technologies [69], [66] [24].*

Technology	**Zigbee**	**Bluetooth**	**RFID**	**Wi-Fi**	
Standard	IEEE 802.15.4	IEEE 802.15.1	ISO 18000	802.11a/b/g/n/ac	IEEE 802.11ah
Frequency band	868/915MHz; 2.4 GHz	2.4GHz	125kHz to 2.5GHz	2.4GHz; 5GHz	Sub-1 GHz
Data rate	250kbps	1 Mbps	1-200 kbps	1Mbps-1 Gbps	0.65 - 7.8 Mbps
Typical Range	10-100 m	10 -30 m	6 m (Passive) 120 m (Active)	100 m	100 - 1000 m
TX power	(-25)-0 dBm	1 - 10 mW	1 mW - 4W	100 mW	1 mW
No.of channels	1/10; 16	79	4(865 MHz band)	14(2.4GHz)	4,2 (868 MHz band)
Bandwidth	0.3/0.6; 2 MHz	1 MHz	200 KHz (865 MHz band)	20; 40; 80MHz	1,2,4,8,16MHz
Modulation	BPSK(+ASK), OQPSK	GFSK	ASK/FSK/PSK	BPSK, QPSK, COFDM, CCK, M-QAM	BPSK, QPSK, 16/64/256-QAM
Transmission technique	DSSS	FHSS	FHSS	DSSS, CCK, OFDM	OFDM
Data protection	16-bit CRC	16-bit CRC	16-bit CRC	32-bit CRC	32-bit CRC

Table 4.5: *Comparison study of ZigBee with Wi-Fi and Bluetooth [69], [66].*

Technology	**Zigbee**	**Bluetooth**	**Wi-Fi**
Basic Cell	Star	Piconet	BSS
Extension of Basic Cell	Cluster tree, Mesh	Scatternet	ESS
Maximum Number of Cell nodes	more than 65000	8	2007

5. SIMULATOR DESCRIPTION AND SETTINGS

5.1 The OMNeT++ Simulation Environment

OMNeT++ is a modular-structure simulator with open architecture environment which has powerful graphical user interface support and an embedded simulation kernel. Simulator is useful for modeling the communication protocols, traffics, computer networks, multi-processor and distributed systems [71].

In the following section, different simulators for modeling communication protocols and computer networks are introduced. Then OMNeT++ is introduced and its functionality is explained in details. In the end, the settings of the simulation are illustrate in details.

5.1.1 Available Network Simulators

A wide variety of simulators are available with different flexibility and complexity to model communication systems and network protocols and simulate their behaviors. Some of the most important simulators are discussed and explained in the following section. More details about network simulator can be found in [71].

OMNeT++ OMNeT++ is a component-based, modular and open source discrete event simulation framework which has the strong GUI and embedded simulation kernel. Different application areas such as computer networks and traffic, complex IT systems, queuing networks, hardware architectures and distributed systems can be simulated by this simulator. In addition, OMNeT++ supports animation and interactive executions. It is an open source simulator and free of charge in order to use for the academic purposes [72].

OPNET A network simulator which provides a solution for network R& D, capacity, and application performance and network operations management. OPNET is specially a development environment that allows to study, design and deploy communication networks, devices, applications and protocols [73].

The Network Simulator-ns2 A leading simulator that accommodates a substantial means for simulation and modeling of TCP, routing and multi-cast proto-

cols over the wire and wireless networks including local and satellite communications. It is developed by University of Southern California (USC) and it is publicly free by GNU GPLv2 license[74].

NetSim NetSim is a popular simulator developed by Tetcos. It is useful for laboratory experimentations and network researches which has turned to be as a teaching tool in academic community. Simulation of many protocols such as aloha, slotted aloha, Ethernet - CSMA/CD, Fast Ethernet, Gigabit Ethernet, Token Ring, Token Bus, W Lan, X.25 Frame Relay, ATM, TCP, IP, Routing RIP, OSPF, BGP, MPLS, Wi-Max, Wireless Sensor Networks and Zigbee 802.15.4 are supported by NetSim. A free demo version can be downloaded from the website [75].

5.1.2 Simulation Modeling Concept

Discrete Event Simulation

Discrete Event Simulation is a simulation in which the state of a model changes only in discrete and random time. The only events can change the states. It should be noticed that between consecutive events, no change in the system is assumed to occur; thus the simulation can directly jump in time from one event to the next one. The time within the simulation is called simulation time and the time when the event occurs is referred to event timestamp. Real time indicates the actual simulation running time which shows how long the simulation takes to completely run.[76].

On the contrary, the states change all the time in continuous simulation model. Most of the systems, for instance, manufacturing, transportation, communications, queuing systems, information processing, and etc can be modeled by applying discrete event simulation. Five different states are investigated in each entity defining the moving unit from one point to another point in the discrete event simulation model:

1. Active state: The state in which the entity is currently moving.

2. Ready state: The state in which the entity is waiting before entering the active state. In other word, more than one entity is in ready state waiting for active state, thus they should move into active state one in a time.

3. Dormant state: Dormant state, hold or sleep state in which the change in the state of the entity cannot be triggered to transfer state. The logic of the model should first transfer the state of the entity from dormant state to ready state.

4. Condition-delayed state: The condition-delayed state is a state in which the entity should wait till a certain condition to be satisfied before enters to ready state.

5. Time-delayed state: The time-delayed state is a state in which the entity should wait for a predetermined amount of time before enters to ready state.

5.1.3 OMNeT++ Introduction

The OMNeT++ is an object-oriented, modular based, and discrete event simulator which is largely used for simulation of communication networks. The OMNeT++ has a component based architecture for modeling systems called module written in C++ language.

OMNeT++ is able to combine simple and compound modules to form a complicated model by using the NED language which is a high level language. There is no limitation in using how many modules in depth for creating a compound module. In addition, it is worth mentioning that OMNeT++ supports a strong GUI and possessing simulation kernel. In OMNeT++, modules communicate via messages which might have sophisticated data structure. These messages can be transferred directly or through a pre-defined route to the destination module. The behavior of the modules can be configured with parameters and by adjusting and tuning the parameters, the modules behavior is modifiable. The simple modules in the OMNeT++ has the duty of the behavioral encapsulation [77].

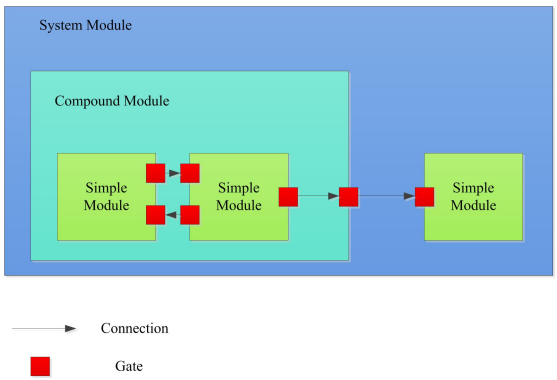


Figure 5.1: *OMNeT++ Model Structure [77].*

Figure 5.1 shows the model structure of the OMNeT++ with the simple and compound modules. As the figure indicates, model consists of sub-modules including simple module and compound module which the number of sub-module nested in the model can be unlimited. In other words, there is no limit in the number of sub-modules in the depth of the nested modules. The simple module, at the lowest level of the module hierarchy in the model, contains the model characteristics described

by the user. The simple modules are written in C++ and by using the OMNeT++ simulation class library.

The OMNeT++ model is called OMNeT++ network as well. The simple and compound modules are instances of user pre-described module types in a network. In the other hand, using the module types, makes it possible to define more sophisticated and complex modules. Thus the OMNeT++ is a suitable tool for describing and modeling the logical structure of an actual system by defining and applying the module types.

5.1.4 The NED Language

NED (NEtwork Description) is a network descriptive language for defining the topology of a network employed by the OMNeT++. This language is a strong tool for describing the simple and compound modules and the channels. The component descriptions defined by the NED can be reused by the other networks using inherited properties of this language. The NED files use the *.ned* extension and the following components:

- Import directives
- Channel definition
- Simple module definition
- Compound module definition
- Network definition

Import Directives

Using import directives, makes it possible to reuse simple and compound modules from another network files . The import directives facilitate using the pre-defined simple modules, compound modules and channel descriptions of another networks in the current network.

Channel Definition

NED allows to define different channel types by sub-classing from the pre-defined channel types. Two channel types can be parametrized to describe common channel attributes. These three types of the channels are described below:

IdealChannel: Ideal channel allows messages to be transferred without delay and impairment along the path. This type of connection has no parameter to configure.

DelayChannel: The propagation delay is taken into account in this channel and two parameters are used to specify the channel attributes:

- *delay:* to simulate the propagation with the unit of second.
- *disabled:*All the messages will be dropped in the case of choosing *true*.

DataRateChannel: Two more parameters are added to *DelayChannel* to specify the data rate and error in the channel:

- *ber* and *per:* BER (bit error rate) and PER (Packet error rate) in the range $[0, 1]$.
- *datarate:* channel bandwidth in bits per second (bps).

The syntax for channel definition is described in the below example:

```
channel ChannelName
// Optional declaration of attributes can be shown here.
```

Parameterizing the pre-defined channel type:

```
channel ChannelName extends ned.DataRateChannel
{
datarate = 50 Mbps;
ber = 1e-10;
delay = 50 us;
}
```

Simple Module Definition

Simple module is the basic unit which contains the network behavior. In the other hand, simple modules are the active elements creating the compound modules. The definition of simple module in the NED consists of parameter and gate declarations. An illustrative example in the below presents the simple module definition in the NED:

```
simple SimpleModuleName

{
  parameters:
  // Declare the simple module variables here.
  gates:
  // Declare in, out and inout gates here.
}
```

Compound Module Definition

Compound modules consist of more than one submodule. These submodules can be simple modules or other compound modules. The most important duty of the compound modules are their flexibility to built the simulation model to be organized and structured, however, the compound modules have no active behavior as simple modules. The definition of the compound modules is the same as the simple modules. The definition of the compound modules is presented in the following. As the figure shows, compound modules have two extra sections including: submodules and connections:

```
module CompoundModule
{    types:
   // Declare any channel and module types which are used locally by
   // the compound module.
   parameters:
   // Declare the compound module variables here.
   gates:
   // Declare in, out and inout gates here.
   submodules:
   // Define the submodules here which the compound module is consisted of.
   connections:
   // Define the connections between all the gates here.
}
```

In the below, the syntax of submodule definition is presented in more details:

```
module CompoundModule
{
 submodules:
   submodule1: ModuleType1 {
     // Define the submodule here .
...
}
   submodule2: ModuleType2 {
     // Define the submodule here.
...
}
}
```

Furthermore, the connections determine the topology of the gates of the compound module and the gates of its submodules which are connected to. In the following, the definition of connections are elaborated in more details:

```
module CompoundModule
{
 submodules:
   connections:
   // Connect output gate with -- >
nodeA.output -- > nodeB.input
   // Connect input gate with < --
nodeA.input < -- nodeB.output
   // Connect inout gate with < -- >
nodeA.inout < -- > nodeB.inout
```

Network Definition

The network definition is necessary to obtain a simulation model which has the executable capability. The network can be instantiated from previously defined compound module. The following example presents the syntax of the network definition:

```
network network extend CompoundModuleTypeA
{
    parameters:
    // Add some parameters
   ....
}
```

5.1.5 Simple Module

Simple modules are the active element in the OMNeT++ in which events occur. The simple modules types are sub-classed from the *cSimpleModule* of the OMNeT++ class library. The *cSimpleModule* has several virtual functions required to be redefined by the user to implement the model behavior.

One of the virtual functions is *handleMessage* which is called whenever the kernel simulation receives a message. In fact, the *handleMessage* is called for every message received by the kernel simulation and the elapsed simulation time during a call to the handleMessage is zero.

The simple modules have a method for the future schedules or timers. The simple simple modules keep themselves busy by sending and receiving a message. Therefore, whenever a module has a future schedule it sends a message to itself. Such a message is called self message. Some of the useful virtual functions are shown in Table 5.1.

Table 5.1: *Send functinons supported by OMNeT++.*

Function	**Description**
send(..)	To send a message through an output gate.
sendDelayed(..)	To send a message through an output gate after a determined delay.
sendDirect(..)	To send a message to a remote destination module without of using any gates or connections.
scheduleAt(..)	To send a self message.

5.1.6 Compound Module

Compound modules comprises of the sub-modules including simple modules and other compound modules. This modules have no active behavior compared to the simple modules. In addition, the compound modules behave like a black box which relay messages by the gates. More details about compound module definition in NED language are addressed in section 5.1.4.

5.1.7 Gates and Connections

Two modules are connected via a pair of gates. The gates have three types: *input*, *output*, and *inout*. Since OMNeT++ only supports one way communication, therefore, for each module should be defined an *inout* gate or an *input* and *output* gate in order to send and receive a message.

The gate definition is a trivial task by listing their name in the gates section of module definition. In addition, the definition of a vector gate which contains a number of single gates allowed by the OMNeT++. A connection is created between starting point (output gate of the source module) and the ending point (input gate of the destination module).

5.1.8 Messages

Messages are the essential concept of the OMNeT++ since each model needs a message or packet to communicate between its modules. In OMNeT++, messages are derived from *cMessage* class which represent events, packets, commands, frames, bits, and etc depending on the model domain. One important function which occurs in the message objects is the encapsulation and decapsulation of the packets. By applying two functions named: *encapsulate()* and *decapsulate()*, the above mentioned functions can be accomplished. The message files have *.msg* extension and the definition of a message can be represent as below:

```
message MyMessage

{
   int srcAddress;
   int destAddress;
   int remainingHops= 30
}
```

5.2 Model Description and Settings

In this work, physical and MAC layer of slotted IEEE 802.15.4 standard is modeled and simulated with OMNeT++. The physical and MAC layers of the standard are described in IEEE 802.15.4 specifications. In the following, simulation environment and scenario in addition to settings of the system-level simulator are discussed in more details.

5.2.1 Simulation Environment

As it mentioned earlier, slotted version of the IEEE 802.15.4 is modeled in this work. The simulated network is star topology meaning that mesh topology and cluster-tree topology are not supported. In star network, STAs send the packets directly to AP without intermediate nodes. It means that, packets arrive to AP in single hop manner. Multi-hop transmission is not addressed here. It is worth mentioning that most M2M and IoT applications will utilize the single hop transmissions. Single hop transmission is superior to multi-hop transmissions in terms of transmission reliability. In addition, single hop transmission imposes less delay than multi-hop transmissions which is very critical in delay sensitive applications.

IEEE 802.15.4 MAC and Physical layer are the main modules which are implemented and modeled. PHY layer implements the following functions:

- Radio implemented in two models: First of all, the three-switch-state model (receiver-on, transmitter-on, turnoff) which facilitates the implementation of MAC-PHY primitives. Second, the four-work-state model (idle, sleep, receiving, and transmitting) in order to perform the energy measurement and carrier sensing tasks.
- Receive and transmission of packets with detection of collision.
- Energy Detection (ED) and Clear channel access function (CCA).
- Implementation of ideal and lossy channel.

MAC layer mostly concentrates on modeling the data transfer function. Besides, these functions are also included:

- Slotted CSMA-CA
- Beacon mode
- Direct, indirect, and GTS data transfer mode
- Inter-frame spacing (IFS), frame filtering and duplication detection
- Association with coordinators

To increase the simulation accuracy, each simulation scenario is independently repeated 100 times and average of results is calculated and plotted as a single point in the graph. The simulation time required for each experiment varies drastically with different traffic and parameters, however, the time for each simulation is chosen long enough to exchange at least 500 packets between AP and STAs in order to increase accuracy. Figure 5.2 shows one typical deployment of the nodes that are randomly distributed in the playground.

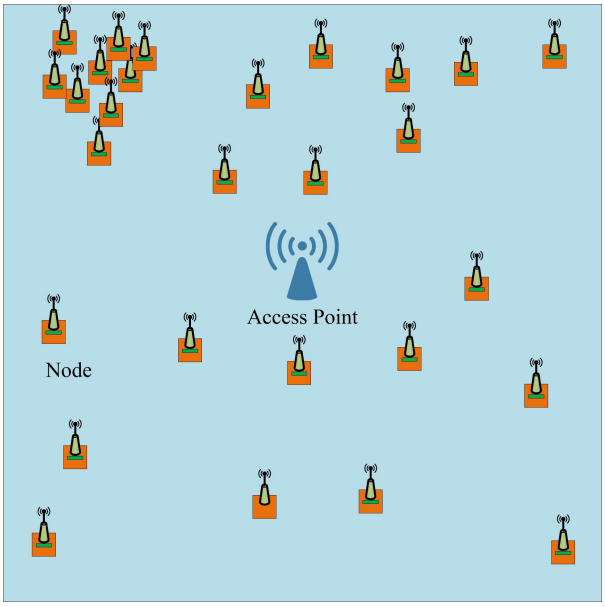


Figure 5.2: *Layout of randomly distributed nodes in the simulations in which AP is located in the center and nodes are randomly distributed throughout the playground.*

Energy consumption is one of the most important concern in designing sensor networks for different applications. The beaconing synchronization mechanism in IEEE 802.15.4 enables networks to work under a controllable duty cycle to achieve better energy efficiency compared to the non-beacon mode. Therefore, the beacon-enabled mode has been chosen in all our simulations.

Table 5.2: *Fixed parameters used in the simulations of the IEEE 802.15.4 basic performance.*

Synchronization mode	beacon-enabled
Topology type	star
Transmitter power	1 mW
Receiver sensitivity	-85 dBm
Thermal noise	-111 dBm
Traffic	Uplink
Size of the playground	64 m * 64 m
Payload size	55 Byte, 115 Byte
macMinBE	3
macMaxBE	5
macMaxCSMABackoffs	4
macMaxFrameRetries	3
Physical Header	5 Bytes
MAC Header	10 Bytes
ACK	11 Bytes
Backoff period	20 Symbols
CCA	8 Symbols

In order to maximize the throughput in IEEE 802.15.4, we assume that beacon interval is very long and no inactive period is utilized; also CFP period are removed. One AP is modeled and all the traffics are uplink meaning that each node transmits the packet to the AP and receives acknowledgment by the AP.

5.2.2 Simulation Parameters

Simulation parameters used in this work are divided into two categories: Fixed parameters which are constant during the whole simulations and parameters which vary from one run to another like the number of nodes and traffic. The fixed parameters are summarized in Table 5.2. In the case of changing a parameter, it will be mentioned.

5.2.3 Energy Consumption Parameters

Energy consumption in wireless technology is a very important metrics in evaluating wireless networks. The energy with the unit of mJ/packet is calculated for sending a correct packet. Table 5.3 wraps up the energy consumption parameters of the simulations in this thesis. These parameters are from CC2420 data sheet [78].

For evaluating energy consumption, the energy of AP is not taken into account because APs do not use battery resources. Therefore, APs are not critical in power

Table 5.3: *Energy consumption parameters in the simulations.*

Energy consumption in transmission	31.31 mW
Energy consumption in receiving	35.46 mW
Energy consumption in idle	0.766 mW
Energy consumption in sleep	180 nW

resource point of view, but in contrast, nodes using the battery have energy constraints.

STAs go to transmission mode whenever they have a packet to send to AP. In this mode, the energy consumption depends on the size of the packet. The bigger packet size the greater energy consumption. STAs switch to receiving mode whenever they receive an ACK frame from the AP which confirms the successful packet delivery. In addition, in idle mode, STAs are in backoff state waiting to send the packet. The STAs delay for random $(2^{BE} - 1)$ unit backoff periods. Whenever STAs have no packet in the buffer, they go to sleeping mode. In the simulation, energy consumption in CCA mode is assumed to be the same as energy consumption in the receiving mode.

5.2.4 Channel and Propagation Loss Model

The propagation model applied for our simulations is based on the outdoor path loss model. The outdoor model has different scenarios, for instance, macro deployment and pico/hotzone deployment. The path loss model employed in this thesis is the macro deployment which is based on [79]. In macro deployment, antenna height is assumed to be 15 meters above the rooftop and the path loss for sub-1 GHz (900 MHz) in dB is given by the following formula:

$$PL(d) = 8 + 37.6log_{10}(d) \tag{5.1}$$

For other frequency bands, the following correction factor shall be added to the above formula:

$$21log_{10}(f/900MHz) \tag{5.2}$$

where d is the distance between transmitter and receiver in meter and f stands for the frequency.

The SNIR is calculated as the ratio of the received signal power to the sum of the thermal noise and interference of the other transmitter's signal. Thermal noise

is calculated based on this equation:

$$P = KTB \tag{5.3}$$

where K refers to Boltzmann's constant, T is the temperature in Kelvin, and B stands for the bandwidth.

SNIR can have different values during receiving the packet because a packet can experience different interferences from other ongoing packet transmissions. For calculating the SNIR in our model, we take into consideration the minimum SNIR during receiving the packet. Figure 5.3 presents how the SNIR is calculated in simulator. As figure shows, the received packet A in the AP has different SNIRs in time-lines a, b, c, and d. The smallest SNIR is calculated as the SNIR for this packet. In addition, AP (receiver) calculates the SNIR values for packet B and packet C which receive after packet A. The AP detects the packet with higher SNIR. For instance, during detection packet A, if the packet B would be stronger than A then AP will neglect packet A and switch to packet B and vice versa.

Based on the IEEE 802.15.4 standard, the SNIR is related to bit error rate (BER) for the OQPSK modulation in 2.4 GHz frequency band as following:

$$BER = \frac{8}{15} \times \frac{1}{16} \times \sum_{k=2}^{16} -1^k \binom{16}{k} e^{\left(20 \times SNIR \times \left(\frac{1}{k} - 1\right)\right)} \tag{5.4}$$

BER for the BPSK in 915 MHz and 868 MHz frequency bands is given by the formula:

$$BER = 0.5 \times exp(-11.25 \times SNIR) \tag{5.5}$$

On the other hand, packet error rate (PER) for a packet with length of N bits is related to BER as following:

$$PER = 1 - (1 - BER)^N \tag{5.6}$$

5.2.5 Simulation Scenarios

Two main scenarios are studied in this work: ideal channel and lossy channel. Ideal channel has no degradation of transmitted signal power when traveling through the medium. It means that ideal channel does not utilize any path loss model. In other word, the received power in the receiver is equal to transmit power in the

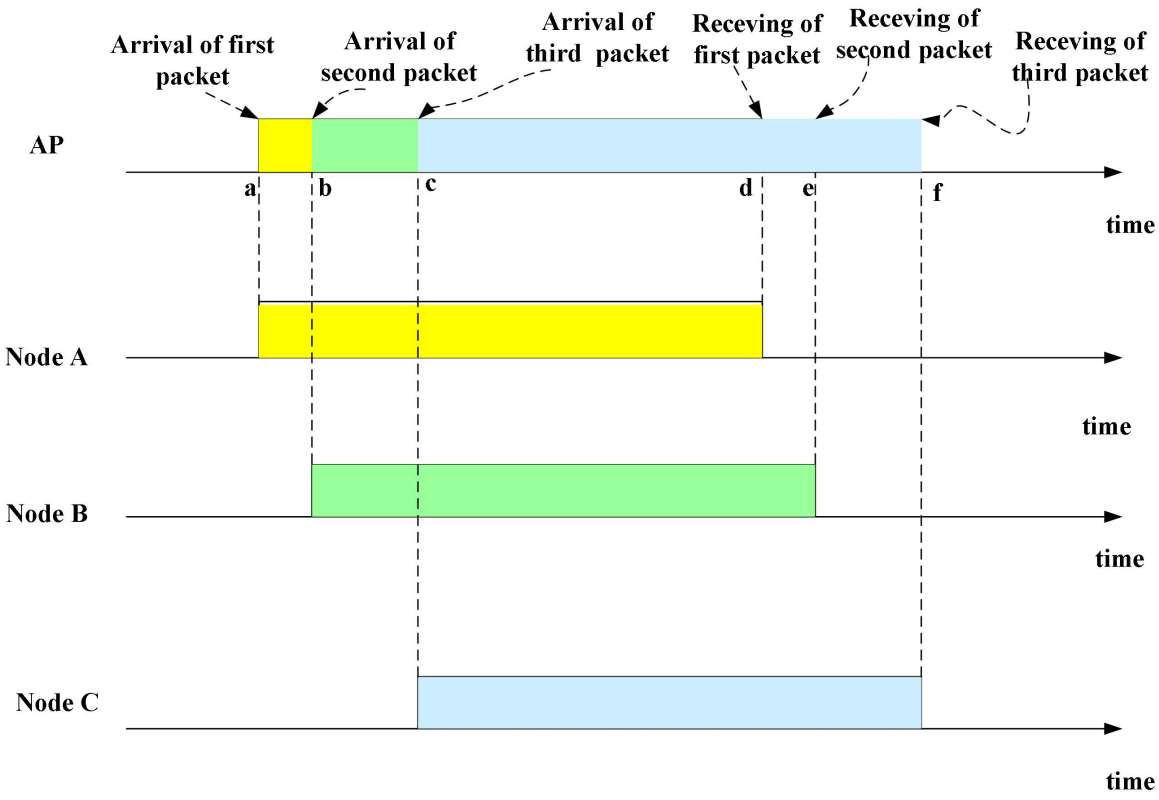


Figure 5.3: *SINR calculation of a received packet taking into account the interference caused by neighboring nodes.*

transmitter. In this scenario, hidden node problem does not exist and each node can hear other nodes in the network.

In lossy channel, the transmission power is faded due to path loss. The path loss can be calculated from a propagation model. In this thesis, the outdoor scenario with macro deployment has been considered.

Each channel scenario is simulated with two different traffic: saturated traffic (or full-buffer traffic) and non-saturated traffic. Saturated traffic means that each node always has a packet to send. In non-saturated traffic, nodes generate the packets with the inter arrival time of 100 ms. The first packet for the nodes is generated with random starting time.

In addition to above mentioned scenarios, the simulations are repeated in three different frequency bands. Based on the IEEE 802.15.4 standard [17], these frequencies are:

- 868 - 868.6 MHz (in Europe)
- 902 - 928 MHz (in North America)
- 2400 - 2483.5 MHz (worldwide)

Many literatures, e.g, [6],[7], [8],[9], simulated and evaluated IEEE 802.15.4 standard in 2.4 GHz but in this work, simulations are performed in all frequency bands defined by the IEEE 802.15.4 standard.

6. SIMULATION PERFORMANCE

The simulation performance of the IEEE 802.15.4 standard, which ZigBee technology uses in its MAC and PHY layers, is comprehensively evaluated in this work. In the literature, this standard is generally investigated in the 2.4 GHz band. This band is world-widely allocated for this technology and most countries employ 2.4GHz frequency. However, other frequency bands exist including 868 MHz allocated in Europe and 915 MHz used in North America. So far, not many works have been carried out in those bands. On the other hand, the new emerging technology like IoT and M2M technologies and demanding requirements such as longer range transmission and coverage pushes the frequency bands to sub-1 GHZ. The simulations are performed in three aforementioned bands in terms of the network throughput, energy consumption, and delay. Furthermore, the performance of slotted IEEE 802.15.4 is compared with IEEE 802.11ah [80], [81]. These comparisons are including the network throughput and energy consumption.

6.1 Simulator Calibration

The entire simulations in this work are accomplished by the OMNeT++. To calibrate our simulator, we compared our simulation results with the analytical model in [82]. The comparison is based on the network throughput in saturated traffic. Two different payloads of 55 bytes and 115 bytes are taken into account. In addition, default parameter value defined for 2.4 GHz frequency channel are considered. Table 6.1 shows the common settings for the calibration.

As Figure 6.1 shows, the simulation results are very closely following the ana-

Table 6.1: *The settings for the simulator calibration.*

packet payload	55 or 115 bytes
Overhead	15 bytes
ACK length	11 bytes
Channel bit rate	250 kbps
Propagation Delay	0
Backoff unit	10 bytes
CCA time	4 byte

lytical model. It means that the employed simulator is reliable for the rest of the simulations.

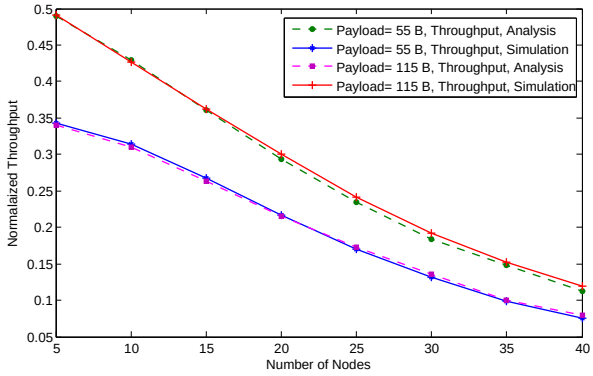
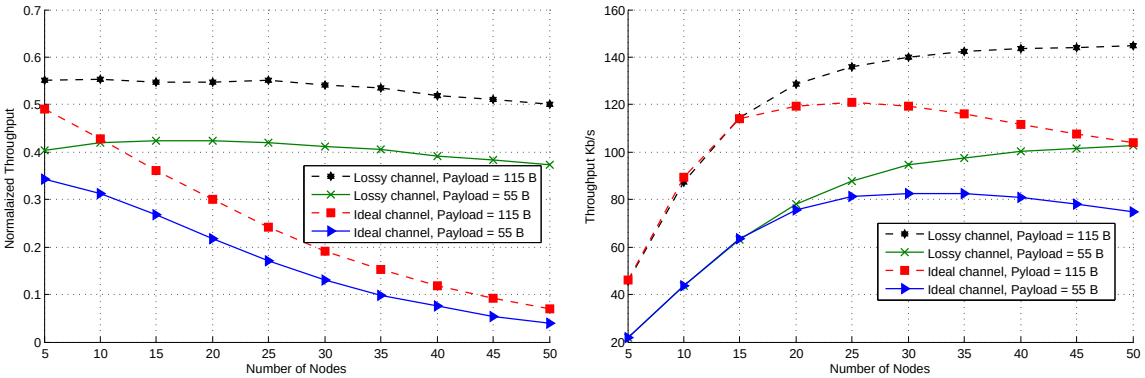


Figure 6.1: *Saturation throughput for validating the simulator.*

6.2 Network Throughput

The throughput is one of the most important metrics to evaluate the network performance. It is defined as the average rate of data packets successfully received at destination node or AP. In other words, throughput provides the ratio of channel capacity used for the successful transmission. The throughput is divided into two main sections of ideal channel and lossy channel. No power degradation exists in ideal channel and each node can hear any other nodes in the vicinity. However, transmission power attenuates in lossy channel due to path loss and other channel impairments. The throughputs are further evaluated in saturated and unsaturated



(a) Normalized throughput in saturated traffic. (b) Throughput in low traffic.

Figure 6.2: *The Network throughput of the IEEE 802.15.4 slotted CSMA/CA in the 2.4 GHz frequency band in ideal and lossy channels with saturated and low traffics.*

traffic. To find the maximum throughput in each scenario, the saturated traffic is employed. This gives the asymptotic capacity of the MAC layer. On the other hand,

in IoT and M2M use cases, the traffic is generally not saturated. Hence, the unsaturated traffic is studied by assuming that the packet are generated following a Poisson distribution with an inter-arrival time of 100 ms. It is worth mentioning that normalized throughput is used to study saturated traffics. The normalized throughput is obtained by dividing the normal throughput by data rate. This metric shows how much of the datarate is used by the entire network to deliver the packets to AP. The normalized throughput is not a fair metrics to be utilized in the unsaturated traffic case.

Figure 6.2 presents the network throughput in the 2.4 GHz frequency band with datarate of 250 kbps. The network throughput is shown in two sub-figures. The normalized throughput in saturated traffic is presented in Figure 6.2(a) and normal throughput in unsaturated traffic is shown in Figure 6.2(b). As figures show,

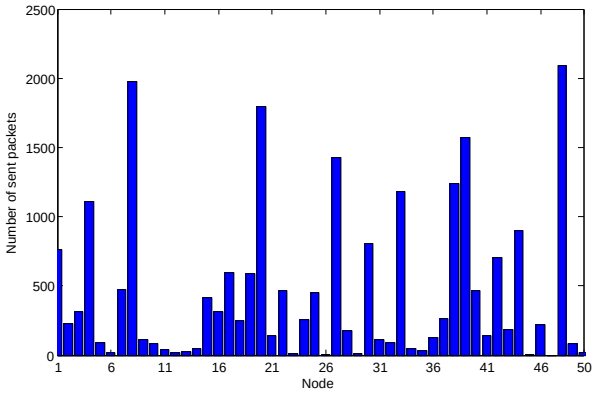


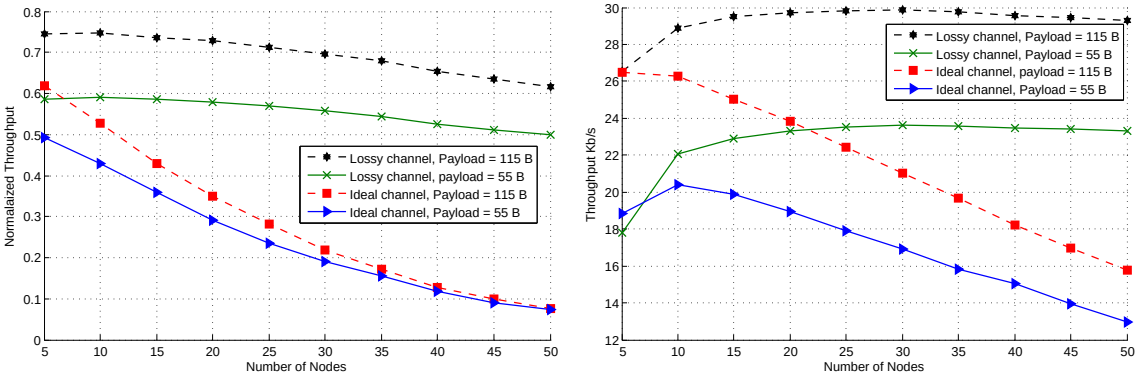
Figure 6.3: *Number of sent packets successfully received by AP in non-ideal channel and saturated traffic (Network with 50 nodes).*

throughputs drastically decrease when the number of nodes increases in ideal channel scenario in both saturated and unsaturated traffics. When the number of nodes increases and since all of them try to get access the medium, collision increases. The higher rate of collision drops the rate of successful transmission, therefore, the throughput drops down. As it obvious from the figures, the bigger the packet size the higher throughput. This pattern occurs for both ideal and lossy channel cases and both saturated and unsaturated traffics.

The non-ideal channel has higher throughput than ideal channel in both saturated and unsaturated traffic. The reduction rate of the throughput in non-ideal channel is much less than ideal channel specially in unsaturated traffic. The reason is that the closer nodes to AP have higher probability to obtain channel access because they present higher SNR. This fact will increase the network throughput but in scarifying the network fairness. The fairness measure is calculated by Raj Jain's equation:

$$F(x_1, x_2, ..., x_n) = \frac{(\sum_{n=1}^{n} x_i)^2}{n. \sum_{n=1}^{n} x_i^2} \tag{6.1}$$

where n is the number of the nodes and x_i is the throughput of the ith node. The fairness is alternating between the range of $1/n$ to 1. $1/n$ is the worst case of the fairness and 1 is the best case in which each node obtains the same throughput. For instance, the fairness measure in the case of a network with 50 nodes and non-ideal channel and saturated traffic is 0.4023. Figure 6.3 shows the number of sent packets for each node. The figure reveals that some of the nodes ,which are far from AP, get less opportunity to access channel.

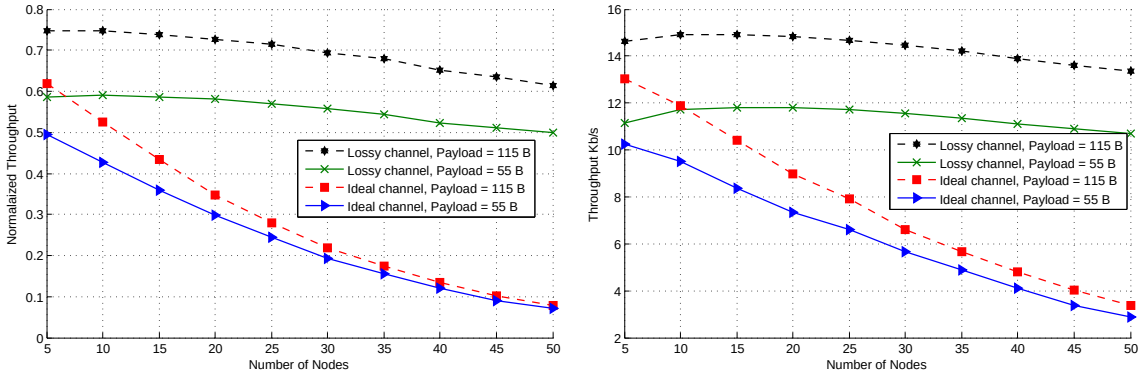


(a) Normalized throughput in saturated traffic.

(b) Throughput in low traffic.

Figure 6.4: *The Network throughput of the IEEE 802.15.4 slotted CSMA/CA in the 915 MHz frequency band in ideal and lossy channels with saturated and low traffics.*

Based on the standard [17], the IEEE 802.15.4 operates in three main frequency bands: 2.4 GHz, 915 MHz, and 868 MHz. Many works has been done in 2.4 GHz with 250 kbps datarate but there is not many works in two other frequency bands. On the other hand, the sub-1 GHz band is an interesting frequency band for IoT and M2M applications due to longer range of transmission. These issues are a motivation to conduct the simulations in 915 MHz and 868 MHz frequency bands with datarate of 40 kbps and 20 kbps, respectively. The throughput results of these bands are shown in Figure 6.4 and 6.5. As the figures show, the throughputs change in the same pattern for these bands. The throughputs in the lossy channel are better than ideal channel in both bands. The rate of reduction of throughput in the ideal channel is sever like the 2.4 GHz frequency band. However, comparison between these sub-1 GHz bands with the 2.4 GHz band reveals one important fact that channel utilization in the sub-1 GHz band is higher than the 2.4 GHz band. It can be seen from comparing the normalized throughput in the saturated traffic in aforementioned bands.

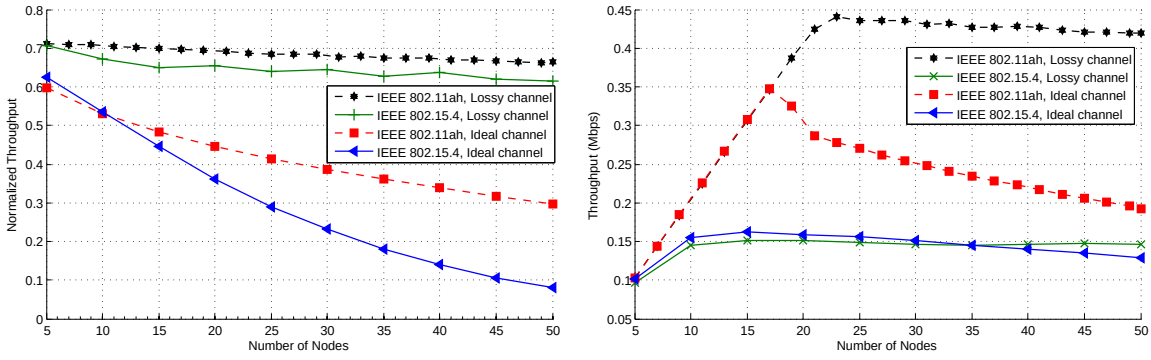


(a) Normalized throughput in saturated traffic. (b) Throughput in low traffic.

Figure 6.5: *The Network throughput of the IEEE 802.15.4 slotted CSMA/CA in the 868 MHz frequency band in ideal and lossy channels with saturated and low traffics.*

The throughput comparison between IEEE 802.15.4 and IEEE 802.11ah is presented in Figure 6.6 in both ideal and non-ideal channel scenarios. In order to have a fair comparison, the payload size of 256 bytes is chosen for both standards and only uplink traffic is taken into account. More details about the simulation setting can be found in [83].

The normalized throughput of two standards in saturated traffic (shown in Figure 6.6(a)) is roughly same for the small number of nodes, however it rapidly drops when the number of nodes is increasing. The rate of the reduction for the IEEE 802.15.4 is more severe compared to the IEEE 802.11ah. Since this figure shows the throughput normalized by the data rate (250 kbps for IEEE 802.15.4 and 0.65 Mbps for IEEE 802.11ah), the difference between two standard is not very sensible. The result for the low traffic in ideal channel is shown in Figure 6.6(b). Throughputs of both standards increases when the number of nodes grows, then it again reduces after the number of nodes reaches to 15 nodes for saturated case and 20 nodes for non-



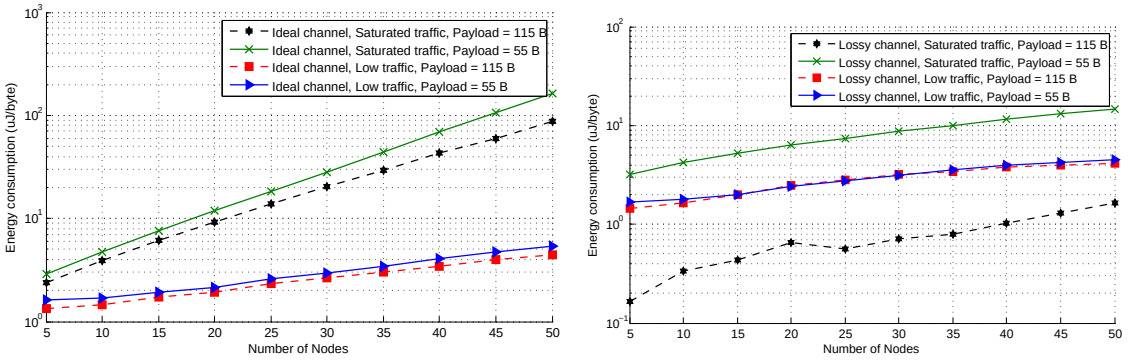
(a) Normalized throughput in saturated traffic. (b) Throughput in low traffic.

Figure 6.6: *The throughput comparison between IEEE 802.11ah and IEEE 802.15.4 in ideal and non-ideal channel with two different traffics: Saturated and non-saturated.*

saturated case. As a result, in a very high number of nodes case, IEEE 802.11ah has better throughput compared to IEEE 802.15.4. The IEEE 802.11ah in lossy channel has better performance specially for congested network.

6.3 Energy Consumption

Energy efficiency is an important factor which recently has drawn many attentions in industry specially in wireless communications. The high number of nodes from one hand and smaller size of the future devices from other hand, encourages the new



(a) Energy consumption to send one byte in ideal channel.

(b) Energy consumption to send one byte in Lossy channel.

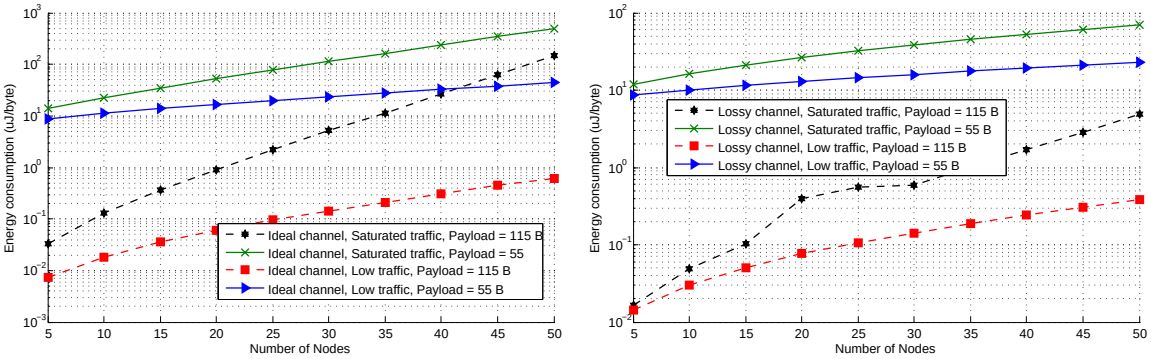
Figure 6.7: *The Average energy consumption (per byte) of the IEEE 802.15.4 slotted CSMA/CA in the 2.4 GHz frequency band in ideal and lossy channel with saturated and low traffic.*

standards to be more energy efficient. In order to investigate energy consumption in this work, the energy consumption of the whole network are taken into account excluding AP. Since AP is using unlimited source of energy, then energy efficiency is not very critical in APs. The energy consumption is determined by the consumed power of the entire network to send a successful byte to the destination.

The energy consumption of the IEEE 802.15.4 in 2.4 GHz frequency band in ideal channel is shown in Figure 6.7(a). The energy consumption to send one byte to destination increases as the number of nodes increases. The increase occurs in both saturated and non-saturated traffic, however, the rate of increment in saturated traffic is much higher than the unsaturated one. The reason is obviously because of the collision growth in the congested network. The figure reveals another fact regarding energy consumption of the network. The energy efficiency when using larger packet sizes is higher than in small packet size cases. In other words, packets with larger size consumes less energy to send one byte rather than packets with smaller size.

Figure 6.7(b) presents the energy consumption in non-ideal channel operated in 2.4 GHz frequency band. The energy efficiency in lossy channel outperforms the ideal

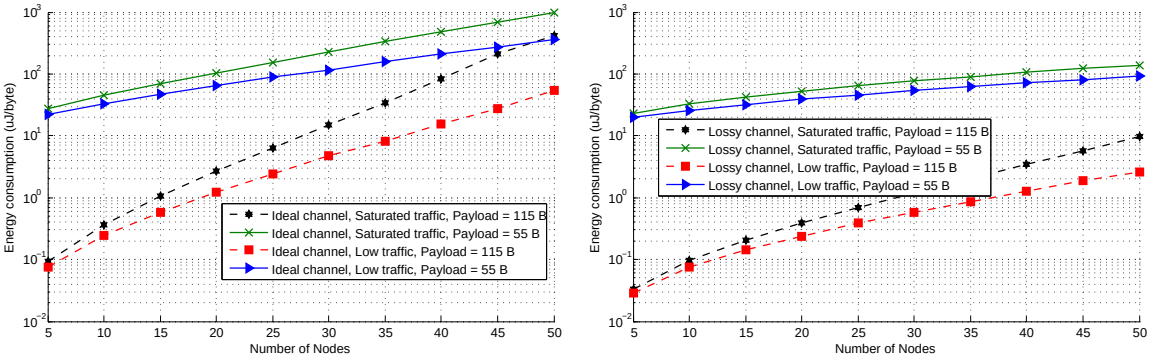
channel in both saturated and low traffic scenarios. One explanation is the higher throughput in non-ideal channel. This means less collision, therefore, less power consumption. As Figure 6.7(b) shows, larger packets are more energy efficient in saturated traffics rather than lower traffics but in the case of smaller packets, it acts vice versa.



(a) Energy consumption to send one byte in ideal channel.

(b) Energy consumption to send one byte in Lossy channel.

Figure 6.8: *The Average energy consumption (per byte) of the IEEE 802.15.4 slotted CSMA/CA in the 915 MHz frequency band in ideal and lossy channel with saturated and low traffic.*



(a) Energy consumption to send one byte in ideal channel.

(b) Energy consumption to send one byte in Lossy channel.

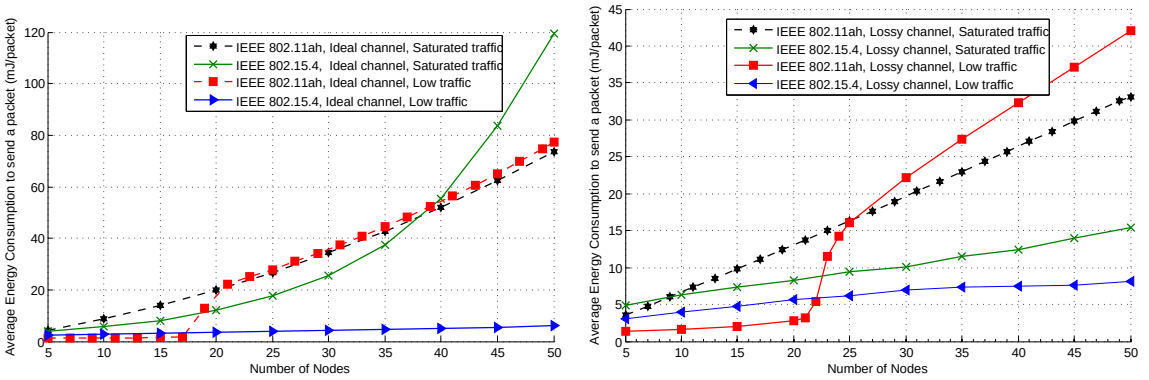
Figure 6.9: *The Average energy consumption (per byte) of the IEEE 802.15.4 slotted CSMA/CA in the 868 MHz frequency band in ideal and lossy channel with saturated and low traffic.*

The energy consumption of the IEEE 802.15.4 operated in 915 MHz and 868 MHz are presented in Figure 6.8 and 6.9. It is assumed the same energy consumption parameters in the above mentioned frequency bands. It is obvious from the figures that in sub-1 GHz more energy is consumed to send one byte to destination compared to 2.4 GHz band. Since the datarate of the 915 MHz and 868 MHz are 40 kbps and 20 kbps ,respectively. Sending one byte of payload is more time consuming than 2.4

Table 6.2: *The common setting for the IEEE 802.11ah and IEEE 802.15.4 comparison.*

Thermal noise	-111 dBm
Energy consumption in Transmission	255 mW
Energy consumption in receiving and channel sensing	135 mW
Energy consumption in idle	1 mW
Size of the payload	256 Bytes
Size of the playground	156 m * 156 m

GHz band. However, this results are concluded from the assumption that all bands use the same power consumption parameters.



(a) Average energy consumption to send a packet in ideal channel.

(b) Average energy consumption to send a packet in Lossy channel.

Figure 6.10: *The energy consumption comparison between IEEE 802.11ah and IEEE 802.15.4 in ideal and non-ideal channel with two different traffics: Saturated and non-saturated.*

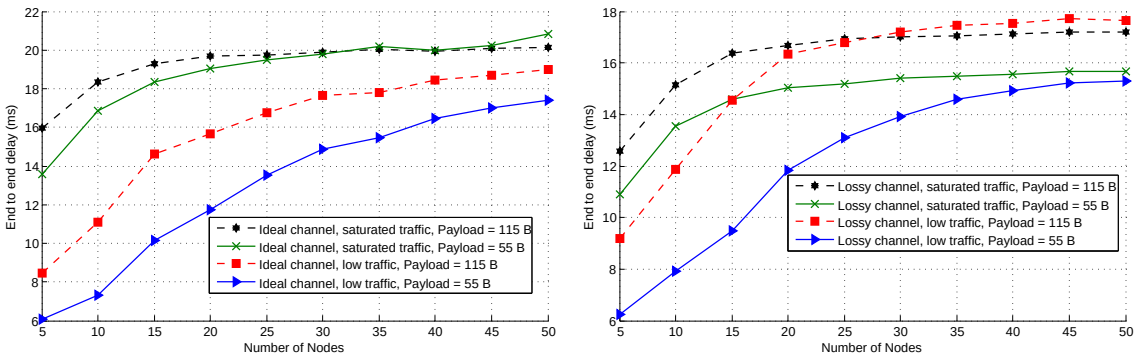
Finally, the energy consumption comparison between IEEE 802.15.4 and IEEE 802.11ah is studied in sub-1 GHz in both ideal and non-ideal channel. The common parameters of the simulation are summarized in Table 6.2. More details about the comparison settings can be found in [83].

Figures 6.10(a) presents the energy consumption in mJ to send a successful packet in ideal channel. Energy consumption of IEEE 802.11ah in saturated traffic is slightly greater than IEEE 80.15.4 for the number of nodes smaller than 40, But it is decreasing when the number of the nodes are increasing. However, the energy consumption in low traffic behaves differently. The IEEE 802.11ah has a slightly smaller energy consumption for number of nodes less than 17 but after that energy consumption is drastically increasing in comparison to the IEEE 802.15.4.

In non-ideal channel, the performance of the IEEE 802.15.4 for high number of nodes is better than IEEE 802.11ah in term of energy consumption. As shown in Figure 6.10(b), IEEE 802.15.4 consumes less energy to send a successful packet in

saturated traffic. It means that this standard is more energy efficient compared to IEEE 802.11ah in this scenario with the above mentioned settings. Figure 6.10(b) also shows the energy consumption in low traffic which indicates better performance of the IEEE 802.15.4 for higher number of nodes. In this scenario, IEEE 802.11ah consumes less energy to send a successful packet.

6.4 Average End-to-end Delay



(a) End-to-end delay in ideal channel.

(b) End-to-end delay in Lossy channel.

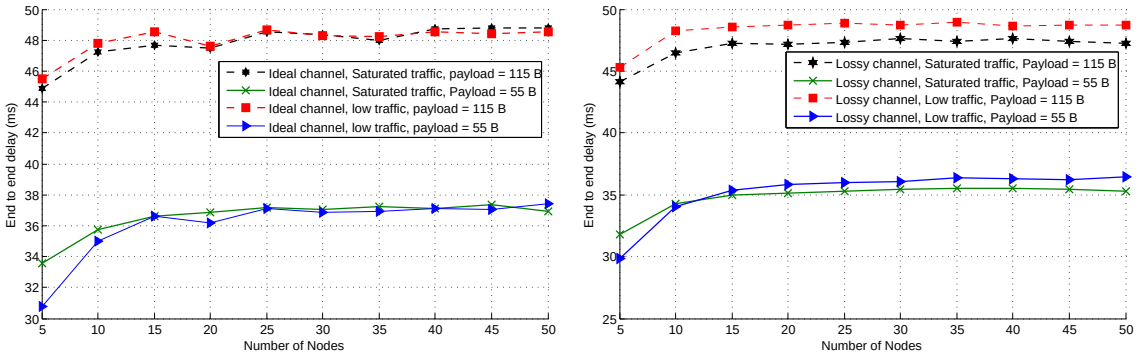
Figure 6.11: *End-to-end delay of the IEEE 802.15.4 slotted CSMA/CA in the 2.4 GHz frequency band in ideal and lossy channel with saturated and low traffic.*

Average end-to-end delay is an important metric to evaluate the networks. This becomes more interesting in the delay sensitive applications. There are wide range of applications such as VOIP which are sensitive to delay. End-to-end delay is defined as the time taken to deliver a packet from source node to the destination node. The delay metric comprises of the following delays: transfer time, queuing, propagation delay, and processing time. In other words, it is defined as the spending time for a packet to travel across a network from source node to destination node which contains all potential delays during propagation delay, processing time, transfer times and delays of retransmission at the MAC layer.

We calculate end-to-end delay in our simulations by the time difference between the creation time of the packet in the application layer of the source node and the time of receiving the Acknowledgment packet of the currently delivered packet. Figure 6.11 present the average end-to-end delay of the IEEE 802.15.4 standard operated in 2.4 GHz band. The figure itself is divided in two sub-figures showing the results for ideal and non-ideal channel. Delay intuitively increase as the number of nodes in the network increases. The figures also reveal that end-to-end delay increase by using the larger packets to send. For instance, delay starts from 16 ms for the packet with 115 bytes size in the saturated traffic and ends to 20 ms. But in the case of 55 bytes payload, it starts from 14 ms and continues till 21 ms. On the

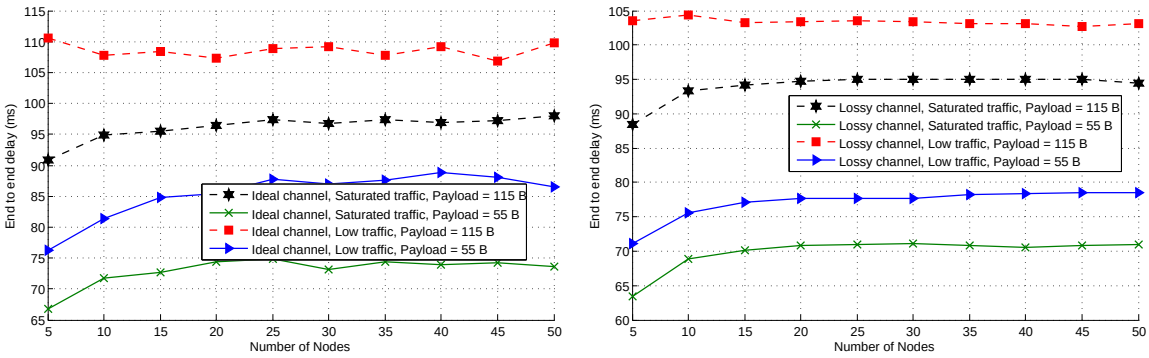
other hand, low traffic network experiences less delay than saturated traffic network.

In non-ideal channel cases which are shown in Figure 6.11(b), nodes generally experience less delay compared to ideal channel scenarios. Low traffic scenarios have less latency than saturated traffic scenarios in non-ideal channel as well.



(a) End-to-end delay in ideal channel. (b) End-to-end delay in Lossy channel.

Figure 6.12: *End-to-end delay of the IEEE 802.15.4 slotted CSMA/CA in the 915 MHz frequency band in ideal and lossy channel with saturated and low traffic.*



(a) End-to-end delay in ideal channel. (b) End-to-end delay in Lossy channel.

Figure 6.13: *End-to-end delay of the IEEE 802.15.4 slotted CSMA/CA in the 868 MHz frequency band in ideal and lossy channel with saturated and low traffic.*

Figures 6.12 and 6.13 present average end-to-end delay in 915 MHz and 868 MHz bands. In both bands, the delay is relatively high which is intuitive because of the low datarate. As Figures 6.12(a) and 6.12(b) show, the saturated traffic has very similar delay as in low traffic case in both ideal and non-ideal channels.

7. CONCLUSIONS

M2M technology is aiming at providing interaction between smart objects extending from sensors, meters, actuators to personal computers, robots, PDAs, and etc without direct intervention of human beings. Furthermore, the number of these devices is exponentially growing. IoT will conduct the large range applications including sensing, communications, networking, computing, information processing, and intelligent control technologies. To work with such environment, applications should satisfy the requirements to enable the M2M communications. Some of these factors are the energy efficiency, delay requirements, and throughput of the applications. The M2M applications are very wide and confront a great variety of requirements. Among the candidate technologies, the IEEE 802.15.4 standard for Low-Rate Wireless Personal Area Networks (WPAN) and the IEEE 802.11 standard for Wireless Local Area Networks (WLAN) are becoming very popular standard in IoT and M2M area.

To make IoT and M2M technology close to reality, wide variety of research should be conducted within these technological area. In this regard, due to importance of the WSNs in future technology and because of the lack of comprehensive research in IEEE 802.15.4, this thesis conducts a thorough study in the performance evaluation of this standard. A system level simulator is developed to analyze and evaluate the performance of this standard in terms of network throughput, energy consumption, and end-to-end delay. The performance evaluation is conducted in frequency bands of 2.4 GHz, 915 MHz, and 868 MHz. Most literatures have been studying this standard in 2.4 GHz and there was a lack of study for Sub-1 GHz band. Sub-1 GHz bands are gaining interest for M2M Applications as an alternative to overcome the propagation and interferences issues at the 2.4 GHz.

The results show that network throughput in lossy channel is higher than ideal channel but in scarifying the network fairness. Due to this fact energy deficiency of the lossy channel is higher than ideal channel. In all frequency bands, the network throughput drops by increasing the number of the nodes in the network and therefore, energy efficiency decreases.

In addition, the performance comparison between IEEE 802.15.4 and IEEE 802.11 ah is conducted in terms of network throughput and energy consumption.

The results of the throughput for the presented settings show that the IEEE

802.11ah outperforms the IEEE 802.15.4 in both idle and non-idle channels with two different traffic cases. In addition, It is shown that in the case of non-ideal channel, both standards have higher throughput compared to ideal channel but in scarifying the transmission fairness. In other words, the nodes which are closer to AP have higher probability to send their packets compared to farther nodes. In term of energy consumption, IEEE 802.15.4 consumes more average energy to send a successful packet compared with the rival standard in the case of small number of nodes in low traffic scenario. In contrast, energy consumption of the IEEE 802.11ah is relatively higher in congested networks. It is concluded that the performance of the IEEE 802.11ah is better in term of throughput but in the case of the energy consumption, the IEEE 802.15.4 still outperforms the IEEE 802.11ah specially in a dense network and non-saturated traffic.

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